# CHAPTER 11

# ENERGY DISSIPATORS

# CHAPTER 11 – TABLE OF CONTENTS

# 11.1 ENERGY DISSIPATORS INTRODUCTION

## 11.1.1 Overview

The failure or damage of many culverts and detention basin outlet structures can be traced to unchecked erosion. Erosive forces, which are at work in the natural drainage network, are often exacerbated by the construction of a highway or by other urban development. Interception and concentration of overland flow and constriction of natural waterways inevitably results in an increased erosion potential. To protect the culvert and adjacent areas, it is sometimes necessary to employ an energy dissipator.

## 11.1.2 Definition

Energy dissipators are any device designed to protect downstream areas from erosion by reducing the velocity of flow to acceptable limits.

## 11.1.3 Purpose

This Chapter provides:

- Design procedures that are based on HEC 14 *(11)*.
- Results of analyses using the HYDRAIN *(10)* system or the HY8 software *(12)*.

## 11.1.4 Symbols

See Table 11-1.

# 11.2 DESIGN CRITERIA

## 11.2.1 Overview

### 11.2.1.1 Policy

Policy is a set of goals that establish a definite course of action or method of action and that are selected to guide and determine present and future decisions (see Policy, Chapter 3). Policy is implemented through design criteria for making decisions.

### 11.2.1.2 Design Criteria

Design criteria are the standards by which a policy is implemented or placed into action. They form the basis for the selection of the final design configuration. Listed below by categories are the design criteria that should be considered for all energy dissipator designs.

## 11.2.2 Dissipator Type Selection

The dissipator type selected for a site must be appropriate to the location. In this Chapter, the terms internal and external are used to indicate the location of the dissipator in relationship to the culvert. An external dissipator is located outside of the culvert, and an internal dissipator is located within the culvert barrel. Table 11-2 provides limitations for each dissipator type and can be used to determine the alternative types to consider.

**TABLE 11-1 — Symbols, Definitions and Units**

| Symbol | Definition | Units |
|---|---|---|
| A | Cross sectional area | $ft^2$ |
| $A_o$ | Area of flow at culvert outlet | $ft^2$ |
| $d_E$ | Equivalent depth at brink | ft |
| $d_o$ | Normal flow depth at brink | ft |
| D | Height of culvert | ft |
| $D_E$ | Equivalent depth at brink | ft |
| $d_{50}$ | Mean diameter of riprap | in |
| DI | Discharge Intensity Modified | — |
| Fr | Froude Number | — |
| $h_S$ | Depth of dissipator pool | ft |
| L | Length of culvert | ft |
| $L_b$ | Bottom width of SAF basin | ft |
| $L_B$ | Overall length of basin | ft |
| $L_T$ | Horizontal distance of SAF upstream slope | ft |
| $L_S$ | Length of dissipator pool | ft |
| Q | Rate of discharge | $ft^3/s$ |
| $S_o$ | Slope of streambed | ft/ft |
| $R_c$ | Ratio of flow area to wetted perimeter | ft |
| TW | Tailwater depth | ft |
| $V_d$ | Velocity downstream | ft/s |
| $V_L$ | Velocity — (L) feet from brink | ft/s |
| $V_o$ | Normal velocity at brink | ft/s |
| $W_o$ | Diameter or width of culvert | in or ft |
| $W_S$ | Width of scour hole | ft |
| $Y_e$ | Length or depth basin-scale characteristic of water or energy | ft |

1. INTERNAL DISSIPATORS. Internal dissipators are used where:

    - the scour hole at the culvert outlet is unacceptable,
    - the right-of-way is limited,
    - debris is not a problem, and
    - moderate velocity reduction is needed.

2. NATURAL SCOUR HOLES. Natural scour holes are used where:

- undermining of the culvert outlet will not occur or it is practicable to be checked by a cutoff wall,

**TABLE 11-2 — Dissipator Limitations (after HEC 14)**

| Dissipator Type | Froude Number (Fr) | Allowable Debris | | | Tailwater (TW) | Special Considerations |
|---|---|---|---|---|---|---|
| | | Silt/ Sand | Boulders | Floating | | |
| Free Hydraulic Jump | > 1 | H | H | H | Required | |
| CSU Rigid Boundary | < 3 | M | L | M | — | |
| Tumbling Flow | > 1 | M | L | L | — | $4 < S_o < 25$ |
| Increased Resistance | — | M | L | L | — | Check Outlet Control HW |
| USBR Type II | 4 to 14 | M | L | M | Required | |
| USBR Type III | 4.5 to 17 | M | L | M | Required | |
| USBR Type IV | 2.5 to 4.5 | M | L | M | Required | |
| SAF | 1.7 to 17 | M | L | M | Required | |
| Contra Costa | < 3 | H | M | M | < 0.5d | |
| Hook | 1.8 to 3 | H | M | M | — | |
| USBR Type VI | — | M | L | L | Desirable | $Q < 400\ ft^3/s$ $V < 50\ ft/s$ |
| Forest Service | — | M | L | L | Desirable | D < 3 ft |
| Drop Structure | < 1 | H | L | M | Required | Drop < 15 ft |
| Manifold | | M | N | N | Desirable | |
| USACE Stilling Well | — | M | L | N | Desirable | |
| Riprap | < 3 | H | H | H | — | Note: N = none<br>L = low<br>M = moderate<br>H = heavy |

- the expected scour hole will not cause costly property damage, and
- there is no nuisance effect.

3. EXTERNAL DISSIPATORS. External dissipators are used where:

- the outlet scour hole is not acceptable;
- moderate amount of debris is present; and
- the culvert outlet velocity ($V_o$) is moderate, Fr < 3.

4. STILLING BASINS. Stilling Basins are used where:

- the outlet scour hole is not acceptable;
- debris is present; and
- the culvert outlet velocity ($V_o$) is high, Fr > 3.

### 11.2.3 <u>Design Limitations</u>

#### 11.2.3.1 Ice Buildup

If ice buildup is a factor, it shall be mitigated by:

- sizing the structure to not obstruct the winter low flow, and
- using external dissipators.

#### 11.2.3.2 Debris Control

Debris control shall be designed using HEC 9 *(8)* and shall be considered:

- where clean-out access is limited, and
- if the dissipator type selected cannot pass debris.

#### 11.2.3.3 Flood Frequency

The flood frequency used in the design of the energy dissipator device shall be the same flood frequency used for the culvert design. The use of a design flood of less magnitude may be permitted, if justified by:

- low risk of failure of the crossing,
- substantial cost savings,
- limited or no adverse effect on the downstream channel, and
- limited or no adverse effect on downstream development.

#### 11.2.3.4 Maximum Culvert Exit Velocity

The culvert exit velocity shall be consistent with the maximum velocity in the natural channel or shall be mitigated by using:

- channel stabilization; see Channels, Chapter 8; and
- energy dissipation.

#### 11.2.3.5 Tailwater Relationship

The hydraulic conditions downstream shall be evaluated to determine a tailwater depth and the maximum velocity for a range of discharges:

- Open channels (see Channels, Chapter 8).

- Lake, pond or large water body shall be evaluated using the high-water elevation that has the same frequency as the design flood for the culvert if events are known to occur concurrently (statistically dependent). If statistically independent, evaluate the joint probability of flood magnitudes and use a likely combination.

- Tidal conditions shall be evaluated using the mean high tide but shall be checked using low tide.

### 11.2.4 <u>Design Options</u>

#### 11.2.4.1 Material Selection

The material selected for the dissipator shall be based on a comparison of the total cost over the design life of alternative materials and shall not be made using first cost as the only criteria. This comparison shall consider replacement cost and the difficulty of construction and traffic delay.

#### 11.2.4.2 Culvert Outlet Type

In choosing a dissipator, the selected culvert end treatment has the following implications:

- Culvert ends that are projecting or mitered to the fill slope offer no outlet protection.
- Headwalls provide embankment stability and erosion protection. They provide protection from buoyancy and reduce damage to the culvert.
- Commercial end sections add little cost to the culvert and may require less maintenance, retard embankment erosion and incur less damage from maintenance.
- Aprons do not reduce outlet velocity but, if used, shall extend at least one culvert height downstream. They shall not protrude above the normal streambed elevation.
- Wingwalls are used where the side slopes of the channel are unstable, where the culvert is skewed to the normal channel flow, to redirect outlet velocity or to retain fill.

#### 11.2.4.3 Safety Considerations

Roadside safety considerations with respect to external energy dissipators shall be based on Chapter 3 of Reference *(1)*.

#### 11.2.4.4 Weep Holes

If weep holes are used to relieve uplift pressure, they shall be designed in a manner similar to underdrain systems.

### 11.2.5 <u>Related Designs</u>

#### 11.2.5.1 Culvert

The culvert shall be designed independent of the dissipator design (see Culverts, Chapter 9) with the exception of internal dissipators, which may require an iterative solution. The culvert design shall be completed before the outlet protection is designed and shall include computation of outlet velocity.

#### 11.2.5.2 Downstream Channel

The downstream channel protection shall be designed concurrently with dissipator design (see Channels, Chapter 8).

## 11.3 DESIGN PHILOSOPHY

### 11.3.1 <u>Overview</u>

The energy dissipator design approach used in this Chapter is discussed in the following Sections.

### 11.3.2 <u>Alternative Analysis</u>

The designer shall choose alternatives that satisfy:

- topography, and
- design policies and criteria.

The designer shall analyze alternatives for:

- environmental impact,
- hydraulic efficiency, and
- risk and cost.

The designer shall select an alternative that best integrates engineering, economic and political considerations. The chosen dissipator should meet the selected structural and hydraulic criteria and should be based on:

- construction and maintenance costs,
- risk of failure or property damage,
- traffic safety,
- environmental or aesthetic considerations,
- political or nuisance considerations, and
- land-use requirements.

### 11.3.3 Design Methods

The designer has to choose whether (the choices in all capitals are the methods used in this Chapter):

- to design for LOCAL SCOUR or channel degradation;

- to MITIGATE or monitor erosion problems;

- to use drop structures, internal dissipators, SCOUR HOLES, EXTERNAL DISSIPATORS or STILLING BASINS; and

- to use CHARTS or computer software.

#### 11.3.3.1 Types of Scour

Local Scour

Local scour is the result of high-velocity flow at the culvert outlet and extends only a limited distance downstream.

Channel Degradation

Channel degradation may proceed in a fairly uniform manner over a long length or may be evident in one or more abrupt drops (headcuts) progressing upstream with every runoff event:

- It should be investigated as an essential part of the site investigation.
- It should be mitigated and included in the initial construction (see Channels, Chapter 8).
- It is usually controlled with drop structures.

### 11.3.3.2 Scour Hazard

Mitigated

The scour hazard shall be designed by providing protection at the culvert outlet:

- Initial protection shall be sufficient to provide some assurance that extensive damage could not result from one design runoff event.
- Protection should be inspected after major storms to determine if protection must be increased or extended.

Monitored

The only protection provided is the cutoff walls or culvert end section. The site should be inspected after major storm events to determine if protection is needed.

### 11.3.3.3 Dissipator Types

Scour Holes

Details of the design of scour holes area are as shown in Section 11.4.4.

Internal Dissipators

- tumbling flow,
- increased resistance, and
- broken-back culverts.

This Chapter does not include details of the design of Internal Dissipators. The designer should refer to HEC 14 *(11)* and Reference *(13)* if design details are needed. An overview of broken-back culvert design is provided in Chapter 9, Appendix 9.F.

External Dissipators

- USBR TYPE VI IMPACT (Section 11.9).
- RIPRAP (Section 11.8).
- CSU rigid boundary (see HEC 14 Reference *(11)*).
- Contra Costa (see HEC 14).
- Hook (see HEC 14).
- Hydraulic jump (see HEC 14).

Stilling Basins

- Saint Anthony Falls (SAF) (Section 11.7).
- USBR Type II (see HEC 14 *(11)*).
- USBR Type III (see HEC 14).
- USBR Type IV (see HEC 14).

Drop Structures

- DROP STRUCTURES (Section 11.10)
- See HEC 23 *(7)*.

#### 11.3.3.4 Computational Methods

Charts

- Charts are required for a manual solution.

- Charts required for the design of scour holes, riprap basin, USBR Type VI impact basin and SAF basin are included in this Chapter. Charts required for the design of other types of energy dissipators are found in HEC 14 *(11)*.

Computer Software

- HY-8 (FHWA Culvert Analysis Software), Version 4.1 or greater Reference *(12)*, contains an energy dissipator module that can be used to analyze most types of energy dissipators in HEC 14.

## 11.4 DESIGN EQUATIONS

### 11.4.1 General

An exact theoretical analysis of flow at culvert outlets is extremely complex because the following data is required:

- analyzing non-uniform and rapidly varying flow,
- applying energy and momentum balance,
- determining where a hydraulic jump will occur,
- applying the results of hydraulic model studies, and
- consideration of temporary upstream storage effects.

### 11.4.2 Approach

The design procedures presented in this Chapter are based on the following:

- Model studies were used to calibrate the equations and charts for scour hole estimating and energy dissipator design.

- HEC 14 *(11)* is the base reference and contains full explanation of all the equations and procedures used in this Chapter, with the exception of those discussed in Section 11.4.3.

### 11.4.3 Culvert Outlet Conditions

The culvert design establishes the outlet flow conditions. However, these parameters may require closer analysis for energy dissipator design.

Depth (ft) ($d_o$)

- The normal depth assumption should be reviewed and a water surface profile calculated if L < $50d_o$.
- The brink depth (see HEC 14 *(11)* for curves) should be used for mild slopes and low tailwater, not critical depth.

Area (ft$^2$) ($A_o$)

The cross sectional area of flow at the culvert outlet should be calculated using ($d_o$).

Velocity (ft/s) ($V_o$)

The culvert outlet velocity should be calculated as follows:

$$V_o = Q/A_o \quad (11.1)$$

where: Q = discharge, ft$^3$/s

Froude Number (Fr)

The Froude number is a flow parameter that has traditionally been used to design energy dissipators and is calculated using:

$$Fr = V_o/[(gd_o)^{0.5}] \quad (11.2)$$

where: g = acceleration of gravity, 32.2 ft/s$^2$

Equivalent Depth (ft) ($d_E = (A_o/2)^{0.5}$)

Equivalent depth is an artificial depth that is calculated for culverts which are not rectangular so that a reasonable Fr can be determined.

Discharge Intensity ($DI_c$)

Discharge intensity is a flow parameter similar to Fr that is used for circular culverts of diameter (D) that are flowing full:

$$DI_c = Q/(g^{0.5}D^{2.5}) \quad (11.3)$$

Discharge Intensity Modified (DI)

Referring to Chapter 5, HEC 14 *(11)* the Modified Discharge Intensity, DI, for all culvert shapes are:

$$DI = Q/(g^{0.5}\ R_c^{2.5}) \quad (11.4)$$

where:
- Q = discharge, ft$^3$/s
- $R_c$ = ($A_c/P_c$), ft
- $A_c$ = flow area, ft$^2$
- $P_c$ = wetted perimeter, ft

### 11.4.4 Scour Hole Estimation

Chapter 5 of HEC 14 *(11)* contains an estimating procedure for scour hole geometry based on soil, flow data and culvert geometry. This scour prediction procedure is intended to serve together with the maintenance history and site reconnaissance information for determining energy dissipator needs.

Only scour hole on cohesionless material will be discussed in this Chapter. For scour hole on cohesive soil, the designer can refer to Chapter 5, HEC 14 *(11)* for details.

The results of the tests made by the US Army Waterways Experiment Station, Vicksburg, Mississippi indicate that the scour hole geometry varies with the tailwater conditions. The maximum scour geometry occurs at tailwater depths less than half the culvert height. The maximum depth of scour, $d_S$, occurs at a location approximately $0.4L_S$ downstream of the culvert, where $L_S$ is the length of the scour.

The following empirical equations (*(2)*, *(16)*) defining the relationship between the culvert discharge intensity, time and the length, width, depth and volume of the scour hole are presented for the maximum or extreme scour case, where:

$d_S$ = maximum depth of scour hole, ft
$L_S$ = length of scour hole, ft
$W_S$ = width of scour hole, ft

$$\left[\frac{d_s}{R_c}, \frac{W_s}{R_c}, \frac{L_s}{R_c}\right] = C_s C_h \left(\frac{\alpha}{\sigma^{1/3}}\right)\left(\frac{Q}{\sqrt{g}R_c^{2.5}}\right)^{\beta}\left(\frac{t}{316}\right)^{\theta} \tag{11.5}$$

$$d_s, W_s \text{ or } L_s = (F_1)(F_2)(F_3)R_c \tag{11.6}$$

where:

$$F_1 = C_s C_h \left(\frac{\alpha}{\sigma^{1/3}}\right)$$

$$F_2 = \left(\frac{Q}{\sqrt{g}R_c^{2.5}}\right)^{\beta} = (DI)^{\beta}$$

$$F_3 = \left(\frac{t}{316}\right)^{\theta}$$

where:
$t$ = 30 min or the time of concentration, if longer
$R_c$ = hydraulic radius of the flow at the exit of the culvert
$\sigma$ = material standard deviation; generally, $\sigma$ = 2.10 for gravel and 1.87 for sand
$\alpha$, $\beta$, $\theta$, $C_s$ and $C_h$ are coefficients, as shown in Table 11-3
$F_1$, $F_2$ and $F_3$ are factors to aid the computation, as shown in Step 7B, Figure 11-1

**TABLE 11-3 — Coefficients**

A. Coefficient for Culvert Outlet Scour (Cohesionless Materials)

| | $\alpha$ | $\beta$ | $\theta$ |
|---|---|---|---|
| Depth, $d_S$ | 2.27 | 0.39 | 0.06 |
| Width, $W_S$ | 6.94 | 0.53 | 0.08 |
| Length, $L_S$ | 17.10 | 0.47 | 0.10 |
| Volume, $V_S$ | 127.08 | 1.24 | 0.18 |

B. Coefficient $C_S$ for Outlets Above the Bed

| $H_S$ | Depth | Width | Length | Volume |
|---|---|---|---|---|
| 0 | 1.00 | 1.00 | 1.00 | 1.00 |
| 1 | 1.22 | 1.51 | 0.73 | 1.28 |
| 2 | 1.26 | 1.54 | 0.73 | 1.47 |
| 4 | 1.34 | 1.66 | 0.73 | 1.55 |
| $H_S$ is the height above bed in pipe diameters, ft | | | | |

C. Coefficient $C_h$ for Culvert Slope

| Slope % | Depth | Width | Length | Volume |
|---|---|---|---|---|
| 0 | 1.00 | 1.00 | 1.00 | 1.00 |
| 2 | 1.03 | 1.28 | 1.17 | 1.30 |
| 5 | 1.08 | 1.28 | 1.17 | 1.30 |
| >7 | 1.12 | 1.28 | 1.17 | 1.30 |

## 11.5 DESIGN PROCEDURE

Overview

The following design procedures are intended to provide a convenient and organized method for designing energy dissipators by hand. The designer should be familiar with all equations in Section 11.4 before using these procedures. In addition, application of the following design method without an understanding of hydraulics can result in an inadequate, unsafe or costly structure:

Step 1 Assemble Site Data And Project File

a. See culvert design file for site survey.
b. Review Section 11.2.2 for applicable criteria.

Step 2 Determine Hydrology

See culvert design file.

Step 3 Select Design (Q)

a. See Section 11.2.3 “Design Limitations.”
b. See culvert design file.
c. Select flood frequency.
d. Determine Q from frequency plot (Step 2).

Step 4 Review Downstream Channel

a. See culvert design file.
b. Determine channel slope, cross section, normal depth and velocity.
c. Check bed and bank material stability.

Step 5 Review Culvert Design

See culvert design file and obtain design discharge, outlet flow conditions (velocity and depth), culvert type (size, shape and roughness), culvert slope and performance curve.

Step 6 Summarize Data On Design Form

a. Use Figure 11-1 “Energy Dissipator Checklist.”
b. Enter data from Steps 1-5 into Figure 11-1.

Step 7 Estimate Scour Hole Size

a. Enter input for scour equation on Figure 11-1.
b. Calculate $d_S$, $W_S$, $L_S$, using Equation 11.5 or 11.6.

Step 8 Determine Need For Dissipator

An energy dissipator is needed if:

a. the estimated scour hole dimensions that exceed the allowable right-of-way, undermines the culvert cutoff wall or presents a safety or aesthetic problem;

b. downstream property is threatened; or

c. $V_o$ is much greater than $V_d$.

Step 9 Select Design Alternative

a. See Section 11.2.4 “Design Options.”
b. Calculate Froude number, Fr.
c. Choose energy dissipator types:

Project No. ______________________________
Designer ______________________ Date ____________
Reviewer ______________________ Date ____________

| SCOUR EQUATIONS |
|---|
| $\left[\frac{d_s}{R_c}, \frac{W_s}{R_c}, \frac{L_s}{R_c}\right] = C_s C_h \left(\frac{\alpha}{\sigma^{1/3}}\right)\left(\frac{Q}{\sqrt{g}R_c^{2.5}}\right)^{\beta}\left(\frac{t}{316}\right)^{\theta}$ |
| $d_S, W_S, L_S = [C_S C_h \alpha/\sigma^{1/3}][DI]^{\beta}[t/316]^{\theta} R_c$ |
| $d_S, W_S, L_S = [F_1]\,[F_2]\,[F_3]\,R_c$ |

| STEP 7A - EQUATION INPUT DATA | |
|---|---|
| FACTOR | VALUE |
| Q = Discharge, $ft^3/s$ | |
| $A_c$ = Flow area, $ft^2$ | |
| $P_c$ = Wetted Perimeter, ft | |
| $R_c$ = $A_c$ / $P_c$ | |
| DI = Discharge Intensity | |
| t = time of concentration | |

| STEP 6 - DATA SUMMARY | | |
|---|---|---|
| Parameters | Culvert | Channel |
| Station | | |
| Control | | |
| Type | | |
| Height, D | | |
| Width, B | | |
| Length, L | | |
| Material | | |
| Manning's n | | |
| Side Slope | | |
| Discharge, Q | | |
| Depth, d | | |
| Velocity, V | | |
| $Fr=V/(gd)^{0.5}$ | | |
| Flow Area, A | | |
| Slope | | |

| STEP 7B - SCOUR COMPUTATION | | | |
|---|---|---|---|
| Factor | Depth | Width | Length |
| $\alpha$ | 2.27 | 6.94 | 17.10 |
| $\beta$ | 0.39 | 0.53 | 0.47 |
| $\theta$ | 0.06 | 0.08 | 0.10 |
| $F_1$ | | | |
| $F_2$ | | | |
| $F_3$ | | | |
| $[F_1][F_2][F_3]R_c$ | | | |
| Allowable | | | |

If calculated scour > allowable and:

1. Fr > 3, design a SAF basin
2. Fr < 3, design a riprap basin
3. Q < 425 $ft^3/s$, design a USBR Type VI

**FIGURE 11-1 — Energy Dissipator Checklist**

- If Fr > ((3)), design a SAF stilling basin.

- If Fr < ((3)), design a riprap basin, or design a USBR Type VI, if Q < 400 $ft^3/s$ for each barrel and little debris is expected. If these are not acceptable or economical, try other dissipators in HEC 14 *(11)*.

Step 10 Design Dissipators

Use the following design procedures and charts:

- Section 11.7 for the SAF.
- Section 11.8 for the RIPRAP.
- Section 11.9 for the USBR Type VI.

Step 11 Design Riprap Transition

a. Most dissipators require some protection adjacent to the basin exit.

b. The length of protection can be judged based on the difference between $V_o$ and $V_d$. The riprap should be designed using Chapter 17 “Bank Protection” and HEC 11 *(9)*.

Step 12 Review Results

a. If downstream channel conditions (velocity, depth and stability) are exceeded, either:

   - design riprap for channel, Step 4; or
   - select another dissipator, Step 9.

b. If preferred energy dissipator affects culvert hydraulics, return to Step 5 and calculate culvert performance.

c. If debris-control structures are required upstream, consult HEC 9 *(8)*.

d. If a check Q was used for the culvert design, assess the dissipator performance with this discharge.

Step 13 Documentation

a. See Chapter 4.
b. Include computations in culvert report or file.

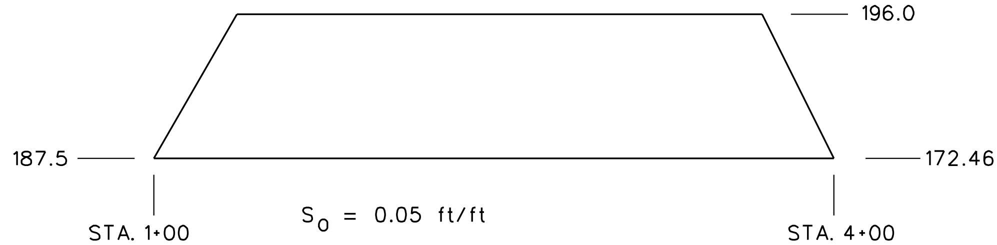
## 11.6 DESIGN EXAMPLE

### 11.6.1 Design Example Steps

The following Example problem uses the culvert data provided in the Culvert Chapter, Section 9.7:

Step 1 Assemble Site Data And Project File

a. Site survey — The culvert project file contains USGS, site and location maps, roadway profile and embankment cross sections. Site visit notes indicate no sediment or debris problems and no nearby structures.




b. Studies by other agencies — none.

c. Environmental, risk assessment show no problems.

d. Design criteria:

- 50-yr frequency for design, and
- 100-yr frequency for check.

Step 2 Determine Hydrology

USGS regression equations yield:

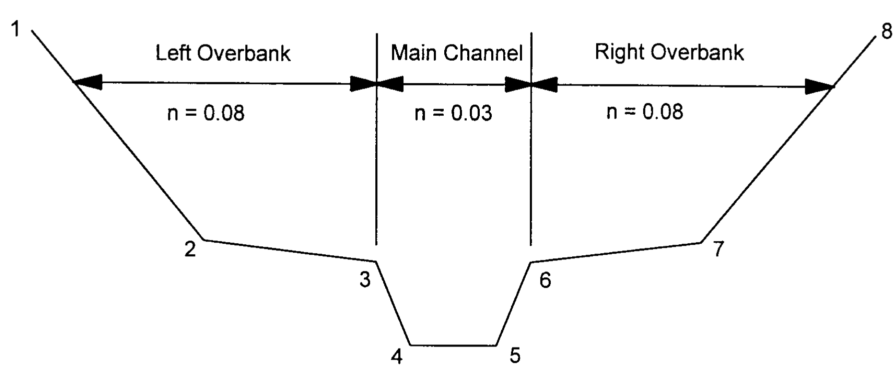
- $Q_{50}$ = 400 $ft^3/s$
- $Q_{100}$ = 500 $ft^3/s$

Step 3 Select Design (Q)

Use $Q_{50}$ = 400 $ft^3/s$, as requested by the design criteria.

Step 4 Design Downstream Channel

a. Cross section of channel with slope = 0.05 ft/ft:



| Point | Station, ft | Elevation, ft |
|---|---|---|
| 1 | 12 | 180.0 |
| 2 | 22 | 175.0 |
| 3 | 32 | 174.5 |
| 4 | 34 | 172.5 |
| 5 | 39 | 172.5 |
| 6 | 41 | 174.5 |
| 7 | 51 | 175.0 |
| 8 | 61 | 180.0 |

b. Rating Curve for Channel:

Calculating normal depth yields:

| Q ($ft^3/s$) | TW (ft) | V (ft/s) |
|---|---|---|
| 100 | 1.41 | 12.18 |
| 200 | 2.11 | 15.34 |
| 300 | 2.55 | 17.74 |
| 400 | 2.87 | 19.34 |
| 500 | 3.14 | 20.68 |

c. At a $V_{50}$ = 19.34 ft/s, the 3-in gravel material that makes up the channel boundary is not stable and riprap is needed (see Channels, Chapter 8) for a transition.

Step 5 Design Culvert

A 7-ft × 6-ft RCB with a beveled entrance on a slope of 0.05 ft/ft was the selected design. The FHWA HY-8 program showed that this culvert is operating at inlet control and has:

| Q ($ft^3/s$) | $HW_i$ (ft) | $V_o$ (ft/s) |
|---|---|---|
| $Q_{50}$ = 400 | 7.43 | 28.24 |
| $Q_{ot}$ = 430 | 7.93 | 28.63 |
| $Q_{100}$ = 500 | 9.14 | 29.48 |

Step 6 Summarize Data On Design Form

See Figure 11-2.

Step 7 Size Scour Hole

The size of the scour hole is determined using Equations 11.5 and 11.6. For channel with gravel bed, the standard deviation of the material, $\sigma$ is 2.10. Table 11-3 shows that the value of $C_S$ =1.00 and $C_h$ = 1.08. See Figure 11-2 for a summary of the computation.

Step 8 Determine Need For Dissipator

The scour hole dimensions are excessive, and because $V_o$ = 28.24 ft/s is much greater than $V_d$ = 18 ft/s, an energy dissipator is needed.

| | | | |
|---|---|---|---|
| Project No. | I-31(88) over Example Creek | | |
| Designer | PLT | Date | 8/26/1988 |
| Reviewer | DLP | Date | 2/24/2003 |

| SCOUR EQUATIONS |
|---|
| $\left[\frac{d_s}{R_c}, \frac{W_s}{R_c}, \frac{L_s}{R_c}\right] = C_s C_h \left(\frac{\alpha}{\sigma^{1/3}}\right)\left(\frac{Q}{\sqrt{g}R_c^{2.5}}\right)^{\beta}\left(\frac{t}{316}\right)^{\theta}$ |
| $d_S,W_S,L_S = [C_S C_h \alpha/\sigma^{1/3}][DI]^{\beta}[t/316]^{\theta} R_c$ |
| $d_S,W_S,L_S = [F_1]\ [F_2]\ [F_3]\ R_c$ |

| STEP 6 - DATA SUMMARY | | |
|---|---|---|
| Parameters | Culvert | Channel |
| Station | 125+50 | 4+00 |
| Control | Inlet | Super. |
| Type | RCB | Natural |
| Height, D | 6 ft | 7.5 ft |
| Width, B | 7 ft | 29 ft |
| Length, L | 300 ft | — |
| Material | Concrete | Gravel |
| Manning's n | 0.012 | 0.03 & 0.08 |
| Side Slope | — | 1V:1H |
| Discharge, Q | 400 $ft^3/s$ | 400 $ft^3/s$ |
| Depth, d | 1.8 ft | 2.8 ft |
| Velocity, V | 28.7 ft/s | 17.6 ft/s |
| $Fr=V/(gd)^{0.5}$ | 3.54 | 2.01 |
| Flow Area, A | 14.0 $ft^2$ | 22.8 $ft^2$ |
| Slope | 0.05 ft/ft | 0.05 ft/ft |

| STEP 7A - EQUATION INPUT DATA | |
|---|---|
| FACTOR | VALUE |
| Q = Discharge, $ft^3/s$ | 400 $ft^3/s$ |
| $A_c$ = Flow area, $ft^2$ | 42 $ft^2$ |
| $P_c$ = Wetted Perimeter, ft | 26 ft |
| $R_c$ = $A_c / P_c$ | 1.62 |
| DI = Discharge Intensity | 1.32 |
| t = time of concentration | 30 min |

| STEP 7B - SCOUR COMPUTATION | | | |
|---|---|---|---|
| Factor | Depth | Width | Length |
| $\alpha$ | 2.27 | 6.94 | 17.10 |
| $\beta$ | 0.39 | 0.53 | 0.47 |
| $\theta$ | 0.06 | 0.08 | 0.10 |
| $F_1$ | 1.92 | 6.94 | 15.62 |
| $F_2$ | 3.28 | 5.03 | 4.19 |
| $F_3$ | 0.87 | 0.83 | 0.79 |
| $[F_1][F_2][F_3]R_c$ | 8.88 | 46.9 | 83.8 |
| Allowable | 7.0* | 29.0* | 60.0* |

If calculated scour > allowable and:

1. Fr > 3, design a SAF basin
2. Fr < 3, design a riprap basin
3. Q < 425 $ft^3/s$, design a USBR Type VI

* *These values are not standards. They may vary, depending on design criteria. In this case, calculated scour > Allowable and Q < 425 $ft^3/s$: Recommend a SAF Basin.*

**FIGURE 11-2 — Energy Dissipator Checklist**

Step 9 Select Design Alternative

Because Fr > 3, an SAF stilling basin should be used.

Step 10 Design Dissipators

The design of an SAF stilling basin is as shown in Section 11.7, Figure 11-3.

Step 11 Design Riprap Transition

Protection is required (see HEC 11 *(9)*).

Step 12 Review Results

The downstream channel conditions are matched by the dissipator.

Step 13 Documentation

a. See Documentation Chapter.
b. Include computations in the culvert report or file.

### 11.6.2 Computer Output

The scour hole geometry can also be computed by using the "Energy Dissipators" module of the FHWA microcomputer program HY-8, Culvert Analysis, Version 6.1 or later (Reference *(12)*). A hardcopy of the output of module is as shown on the next page. The dimensions of the scour hole computed by the HY-8 program are reasonably close to the values calculated in the previous Section.

## 11.7 SAF STILLING BASIN

### 11.7.1 Overview

The St. Anthony Falls (SAF) stilling basin uses a forced hydraulic jump to dissipate energy and:

- based on model studies conducted by NRCS at the St. Anthony Falls (SAF) Hydraulic Laboratory of the University of Minnesota *(4)*;
- uses chute blocks, baffle blocks and an end sill to force the hydraulic jump and reduce jump length by approximately 80%; and
- is recommended where Fr = 1.7 to 17.

### 11.7.2 Equations

#### 11.7.2.1 Basin Width, $W_B$

- For box culvert, $W_B$ = B = culvert width, ft
- For pipe, use $W_B$ = culvert diameter (D), in or ft

<table>
<tr><td colspan="4">FHWA CULVERT ANALYSIS, HY-8, VERSION 6.1</td></tr>
<tr><td>CURRENT DATE<br>02-26-2003</td><td>CURRENT TIME<br>10:56:51</td><td>FILE NAME<br>CULEX1B7</td><td>FILE DATE<br>02-26-2003</td></tr>
<tr><td colspan="4">CULVERT AND CHANNEL DATA</td></tr>
<tr><td colspan="2">CULVERT NO. 1</td><td colspan="2">DOWNSTREAM CHANNEL</td></tr>
<tr><td colspan="2">CULVERT TYPE: 7 ft × 6 ft Box</td><td colspan="2">CHANNEL TYPE: IRREGULAR</td></tr>
<tr><td colspan="2">CULVERT LENGTH = 300.37 ft</td><td colspan="2">BOTTOM WIDTH = 5.00 ft</td></tr>
<tr><td colspan="2">NO. OF BARRELS = 1.0</td><td colspan="2">TAILWATER DEPTH = 2.80 ft</td></tr>
<tr><td colspan="2">FLOW PER BARREL = 400 $ft^3/s$</td><td colspan="2">TOTAL DESIGN FLOW = 400 $ft^3/s$</td></tr>
<tr><td colspan="2">INVERT ELEVATION = 187.50 ft</td><td colspan="2">BOTTOM ELEVATION = 172.50 ft</td></tr>
<tr><td colspan="2">OUTLET VELOCITY = 28.246 ft/s</td><td colspan="2">NORMAL VELOCITY = 17.51 ft/s</td></tr>
<tr><td colspan="2">OUTLET DEPTH = 2.02 ft</td><td colspan="2"></td></tr>
<tr><td colspan="4">SCOUR HOLE GEOMETRY AND SOIL DATA</td></tr>
<tr><td colspan="2">LENGTH = 97.717 ft</td><td colspan="2">WIDTH = 56.561 ft</td></tr>
<tr><td colspan="2">DEPTH = 9.837 ft</td><td colspan="2">VOLUME = 18,036.7 $ft^3$</td></tr>
<tr><td colspan="4">MAXIMUM SCOUR OCCURS 39.087 ft DOWNSTREAM OF CULVERT</td></tr>
<tr><td colspan="4">SOIL TYPE: NONCOHESIVE<br><br>SAND SIZES:<br>D16 = 8 mm<br>D50 = 14 mm<br>D84 = 18 mm</td></tr>
</table>

$$W_B = \frac{0.054Q}{D^{1.5}}\text{, whichever is larger.} \tag{11.7}$$

where: Q = discharge, $ft^3/s$

#### 11.7.2.2 Flare (1:z)

Flare is optional; if used, it should be flatter than 1:2.

#### 11.7.2.3 Basin Length, $L_B$

$$d_j = \frac{d_1}{2}[(1+8Fr_1^2)^{0.5} - 1] \tag{11.8}$$

where:
- $d_1$ = initial depth of water, ft
- $d_j$ = sequent depth of jump, ft
- $Fr_1$ = Froude number entering basin, ≠ Fr

Therefore:

$$L_B = \frac{4.5d_j}{Fr_1^{0.76}} \tag{11.9}$$

#### 11.7.2.4 Basin Floor

The basin floor should be depressed below the streambed enough to obtain the following depth ($d_2$) below the tailwater:

- For $Fr_1$ = 1.7 to 5.5:

$$d_2 = d_j\left[1.1 - \left(\frac{Fr_1^2}{120}\right)\right] \tag{11.10}$$

- For $Fr_1$ = 5.5 to 11:

$$d_2 = 0.85d_j \tag{11.11}$$

- For $Fr_1$ = 11 to 17:

$$d_2 = d_j\left[1.1 - \left(\frac{Fr_1^2}{800}\right)\right] \tag{11.12}$$

#### 11.7.2.5 Chute Blocks

- Height, $h_1 = d_1$
- Width, $W_1$ = spacing, $W_1 = 0.75d_1$
- Number of blocks = $N_c = W_B/2W_1$, rounded to a whole number
- Adjusted $W_1 = W_2 = W_B/2N_c$
- $N_c$ includes the ½ block at each wall

#### 11.7.2.6 Baffle Blocks

- Height, $h_3 = d_1$
- Width, $W_3$ = spacing, $W_4 = 0.75d_1$
- Basin width at baffle blocks, $W_{B2} = W_B + 2L_B/3z$
- Number of blocks = $N_B = W_{B2}/2W_3$, rounded to a whole number
- Adjusted $W_3 = W_4 = W_{B2}/2N_B$
- Check total block width to ensure that 40% to 55% of $W_{B2}$ is occupied by block
- Staggered with chute blocks
- Space at wall $\geq 0.38d_1$
- Distance from chute blocks ($L_{1\text{-}3}$) = $L_B/3$

#### 11.7.2.7 Other Dimensions

- End Sill Height, $h_4 = 0.07d_j$
- Sidewall Height = $d_2 + 0.33d_j$
- Wingwall Flare = 45°

### 11.7.3 Design Procedure

The design of a St. Anthony Falls (SAF) basin consists of several Steps as follows:

Step 1 Select Basin Type

a. Rectangular or flared.
b. Choose flare (if needed), 1:z.
c. Determine basin width, $W_B$.

Step 2 Select Depression

a. Choose the depth $d_2$ to depress below the streambed, $B_d$.
b. Assume $B_d = 0$ for first trial.

Step 3 Determine Input Flow

a. $d_1$ and $V_1$, using energy equation.
b. Froude number, $Fr_1$.

Step 4 Calculate Basin Dimensions

a. $d_j$ (Equation 11.8).
b. $L_B$ (Equation 11.9).
c. $d_2$ (Equations 11.10, 11.11 or 11.12).
d. $L_S = (d_2 - TW)/S_S$.
e. $L_T = (B_d)/S_T$ (see Figure 11-3).
f. $L = L_T + L_B + L_S$ (see Figure 11-3).

## ST. ANTHONY FALLS (SAF) BASIN

Project No. ______________________________

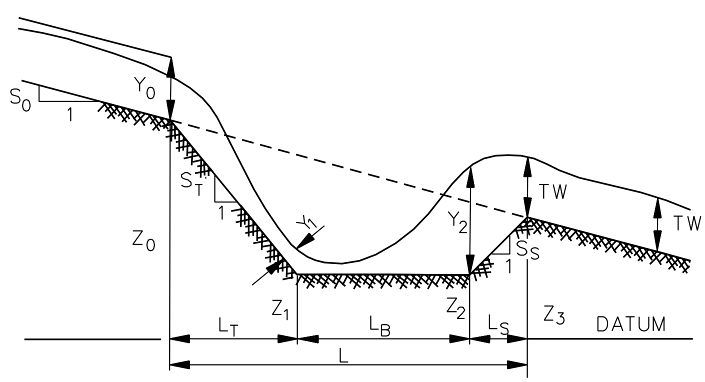
Designer ______________________ Date __________

Reviewer ______________________ Date __________

| SAF BASIN DESIGN VALUES | TRIAL 1 | FINAL TRIAL |
|---|---|---|
| Type | | |
| Flare (Z:1) | | |
| Width, $W_B$ | | |
| Depression, $B_d$ | | |
| $S_S = S_T$ | | |
| Depth, $d_o$ | | |
| Velocity, $V_o$ | | |
| $B_o + d_o + V_o^2/2g$ | | |
| Depth, $d_1$ | | |
| Velocity, $V_1$ | | |
| $Fr_1$ | | |
| $d_j$ | | |
| $L_B$ | | |
| $d_2$ | | |
| $L_S$ | | |
| $L_T = B_d / S_T$ | | |
| $L = L_B + L_S + L_T$ | | |
| $B_d = LS_o + TW$ | | |
| | | |
| | | |

| DIMENSIONS OF ELEMENTS | TRIAL 1 | FINAL TRIAL | DIMENSIONS OF ELEMENTS | TRIAL 1 | FINAL TRIAL |
|---|---|---|---|---|---|
| CHUTE BLOCK | | | BAFFLE BLOCK | | |
| Height, $h_1$ | | | Height, $h_3$ | | |
| Width, $W_1$ | | | Width, $W_3$ | | |
| Spacing, $W_2$ | | | Spacing, $W_4$ | | |
| Block No., $N_C$ | | | Block No., $N_B$ | | |
| END SILL | | | SIDE WALL | | |
| Height, $h_4$ | | | Height, $h_5$ | | |

NOTE: Y = d



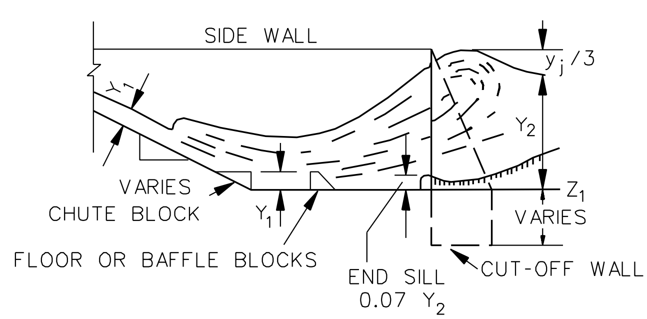




**FIGURE 11-3 —St. Anthony Falls (SAF) Basin Checklist**

Step 5 Review Results

a. If $d_2 \neq (B_d - LS_o + TW)$, return to Step 2.
b. If approximately equal, continue.

Step 6 Size Elements

a. Chute blocks ($h_1$, $W_1$, $W_2$, $N_c$).
b. Baffle blocks ($h_3$, $W_3$, $W_4$, $N_B$, $L_{1\text{-}3}$).
c. End sill ($h_4$).
d. Side wall height ($h_5 = d_2 + 0.33d_j$).

### 11.7.4 Design Example

- See Section 11.6 for input values.
- See Figure 11-4 for completed computation form.

Step 1 Select Basin Type

a. Use rectangular
b. No flare
c. Basin width, $W_B = 7.00$ ft

Step 2 Select Depression (Trial 1)

$B_d = 6.00$ ft, $S_S = S_t = 1$

Step 3 Determine Input Flow (Trial 1)

a. Energy equation (culvert to basin):

Culvert outlet = $B_d + d_o + V_o^2/2g = 6.00 + 2.02 + (28.24)^2/2(32.2) = 20.40$ ft

Basin floor = $0 + d_1 + V_1^2/2g$

Solve: $20.42 = d_1 + V_1^2/2g$

| $d_1$ | $V_1$ | $d_1 + V_1^2/2g$ |
|---|---|---|
| 1.61 | 35.63 | 21.32 > 20.40 |
| 1.64 | 34.91 | 20.56 ≈ 20.40, use |

b. $Fr_1 = 34.91/(1.64 \times 32.2)^{0.5} = 4.80$

Step 4 Calculate Basin Dimensions (Trial 1)

a. $d_j = 10.34$ ft (Equation 11.8)
b. $L_B = 14.13$ ft (Equation 11.9)
c. $d_2 = 9.39$ ft (Equation 11.10)
d. $L_S = (d_2 - TW)/S_S = (9.39 - 2.80)/1 = 6.59$ ft
e. $L_T = (B_d)/S_T = 6.00/1 = 6.00$ ft
f. $L = L_T + L_B + L_S = 6.00 + 14.13 + 6.59 = 26.72$ ft

Step 5 Review Results (Trial 1)

a. If $d_2$ does not equal ($B_d - LS_o + TW$), then adjust drop:

$9.39 \neq (6.00 - 26.72(0.05) + 2.80) = 7.46$ ft

b. Add 9.39 – 7.46 = 1.93 more drop, and return to Step 2.

Step 2 Select Depression (Trial 2)

$B_d = 7.90$ ft, $S_S = S_T = 1$

Step 3 Determine Input Flow (Trial 2)

a. Energy equation (culvert to basin):

Culvert outlet = $B_d + d_o + V_o^2/2g = 7.90 + 2.02 + (28.24)^2/2(32.2) = 22.30$ ft

Basin floor = $0 + d_1 + V_1^2/2g$

Solve: $22.30 = d_1 + V_1^2/2g$

| $d_1$ | $V_1$ | $d_1 + V_1^2/2g$ |
|---|---|---|
| 1.57 | 36.35 | 22.09 ≈ 22.30; use. |

b. $Fr_1 = 36.35/((1.57)(32.2))^{0.5} = 5.11$

Step 4 Calculate Basin Dimensions (Trial 2)

a. $d_j = 10.59$ ft (Equation 11.8)
b. $L_B = 13.79$ ft (Equation 11.9)
c. $d_2 = 9.34$ ft (Equation 11.10)
d. $L_S = (d_2 - TW)/S_S = 6.54$ ft
e. $L_T = (B_d)/S_T = 7.90/1 = 7.90$ ft
f. $L = L_T + L_B + L_S = 7.90 + 13.79 + 6.54 = 28.23$ ft

Step 5 Review Results (Trial 2)

a. $d_2 = 9.34 \approx ((7.90 - 28.23(0.05) + 2.80)) = 9.29$ ft. Is approximately equal, continue.

Step 6 Size Elements (Trial 2)

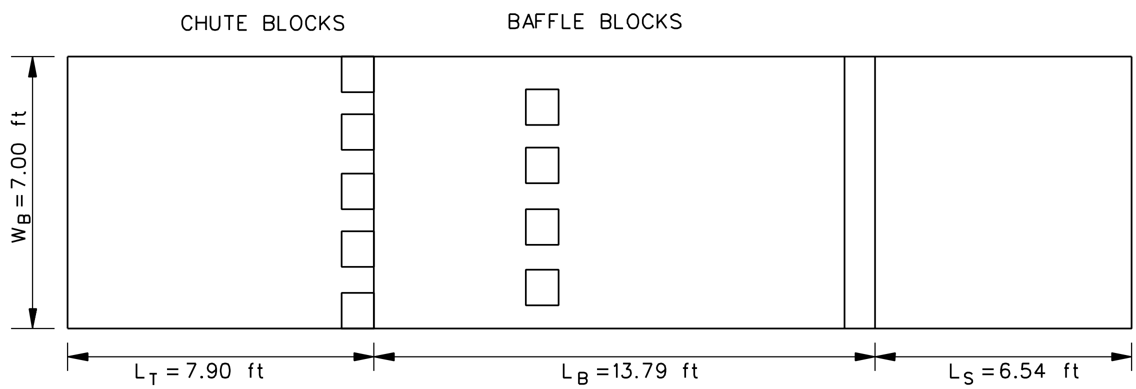
a. Chute blocks ($h_1$, $W_1$, $W_2$, $N_c$):

$h_1 = d_1 = 1.57$ ft
$W_1 = 0.75d_1 = 1.18$ ft
$N_c = W_B/2(W_1) = 7.00/2(1.18) = 2.96$, use 3
Adjusted $W_1 = 7.00/2(3) = 1.17$ ft $= W_2$
Use 2 full blocks, 3 spaces and a half of block at each wall.

b. Baffle blocks ($h_3$, $W_3$, $W_4$, $N_B$, $L_{1\text{-}3}$):
$h_3 = d_1 = 1.57$ ft
$W_3 = 0.75d_1 = 1.18$ ft
Use 3 blocks and, adjusted as above, $W_3 = W_4 = 1.17$ ft
$L_{1\text{-}3} = L_B/3 = 13.79/3 = 4.60$ ft

c. End sill ($h_4$) $= 0.07d_j = 0.07(10.59) = 0.74$ ft

d. Side wall height ($h_5$) $= d_2 + 0.33d_j = 9.34 + 0.33(10.59) = 12.83$ ft




### 11.7.5 <u>Computer Output</u>

The dissipator geometry can be computed using the "Energy Dissipator" module that is available in the microcomputer program HY-8, Culvert Analysis (Reference *(10)*). The output of the culvert and channel input data, and computed geometry using this module, are after Figure 11-4.

## 11.8 RIPRAP BASIN

### 11.8.1 <u>Overview</u>

The riprap basin design is based on laboratory data obtained from full-scale prototypical installations *(18)*. Following are the principal features of the basin:

- Preshaping and lining with riprap of median size, $d_{50}$.
- Constructing the floor at a depth of $h_S$ below the invert, where $h_S$ is the depth of scour that would occur in a pad of riprap of size $d_{50}$.
- Sizing $d_{50}$ so that $2 < h_S/d_{50} < 4$.
- Sizing the length of the dissipating pool to be $10(h_S)$ or $3(W_o)$, whichever is larger for a single barrel. The overall length of the basin is $15(h_S)$ or $4(W_o)$, whichever is larger.
- Angular rock results were approximately the same as the results of rounded material.
- Layout details are shown on Figure 11-5.

ST. ANTHONY FALLS (SAF) BASIN

Project No. Example Problem (US Customary)

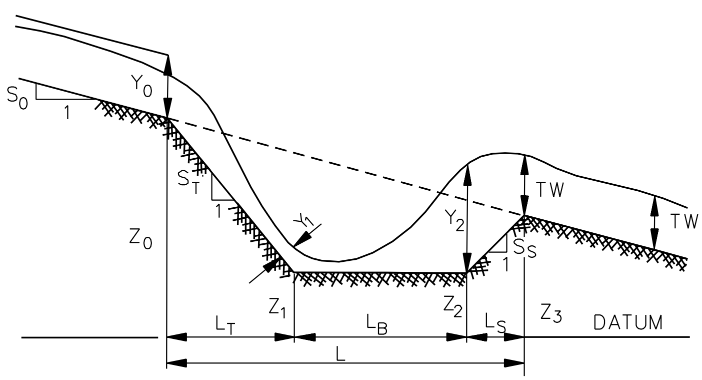
Designer PLT Date

Reviewer DLP Date 2/25/03

| SAF BASIN DESIGN VALUES | TRIAL 1 | FINAL TRIAL |
|---|---|---|
| Type | Rect. | Rect. |
| Flare (Z:1) | 1:1 | 1:1 |
| Width, $W_B$ | 2.13 | 2.13 |
| Depression, $B_d$ | 6.00 | 7.90 |
| $S_S = S_T$ | 1:1 | 1:1 |
| Depth, $d_o$ | 2.02 | 2.02 |
| Velocity, $V_o$ | 28.24 | 28.24 |
| $B_d + d_o + V_o^2/2g$ | 20.40 | 22.30 |
| Depth, $d_1$ | 1.64 | 1.57 |
| Velocity, $V_1$ | 34.91 | 36.35 |
| $Fr_1$ | 4.80 | 5.11 |
| $d_j$ | 10.34 | 10.59 |
| $L_B$ | 14.13 | 13.79 |
| $d_2$ | 9.39 | 9.34 |
| $L_S$ | 6.59 | 6.54 |
| $L_T = B_d / S_T$ | 6.00 | 7.91 |
| $L = L_B + L_S + L_T$ | 26.72 | 28.23 |
| $B_d = LS_o + TW$ | 7.46 | 9.29 |
| | | |
| | | |

| DIMENSIONS OF ELEMENTS | TRIAL 1 | FINAL TRIAL | DIMENSIONS OF ELEMENTS | TRIAL 1 | FINAL TRIAL |
|---|---|---|---|---|---|
| CHUTE BLOCK | | | BAFFLE BLOCK | | |
| Height, $h_1$ | 1.57 | 1.57 | Height, $h_3$ | 1.57 | 1.57 |
| Width, $W_1$ | 1.18 | 1.18 | Width, $W_3$ | 1.18 | 1.18 |
| Spacing, $W_2$ | 1.17 | 1.17 | Spacing, $W_4$ | 1.17 | 1.17 |
| Block No., $N_C$ | 3 | 3 | Block No., $N_B$ | 3 | 3 |
| END SILL | | | SIDE WALL | | |
| Height, $h_4$ | 0.74 | 0.74 | Height, $h_5$ | 12.83 | 12.83 |

NOTE: Y = d



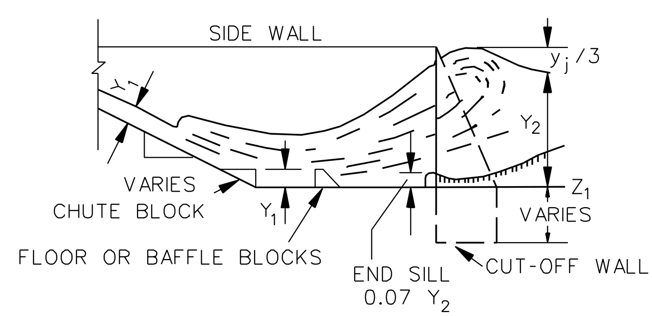




**FIGURE 11-4 — St. Anthony Falls Basin Example Problem**

<table>
<tr><td colspan="4">FHWA CULVERT ANALYSIS, HY-8, VERSION 6.1</td></tr>
<tr><td>CURRENT DATE<br>02-26-03</td><td>CURRENT TIME<br>15:26:05</td><td>FILE NAME<br>CULEX1B7</td><td>FILE DATE<br>02-26-03</td></tr>
<tr><td colspan="4">CULVERT AND CHANNEL DATA</td></tr>
<tr><td colspan="2">CULVERT NO. 1</td><td colspan="2">DOWNSTREAM CHANNEL</td></tr>
<tr><td colspan="2">CULVERT TYPE: 7.00 ft × 6.00 ft</td><td colspan="2">BOX CHANNEL TYPE: IRREGULAR</td></tr>
<tr><td colspan="2">CULVERT LENGTH = 300.37 ft</td><td colspan="2">BOTTOM WIDTH = 5.00 ft</td></tr>
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<tr><td colspan="2">FLOW PER BARREL = 400 $ft^3/s$</td><td colspan="2">TOTAL DESIGN FLOW = 400 $ft^3/s$</td></tr>
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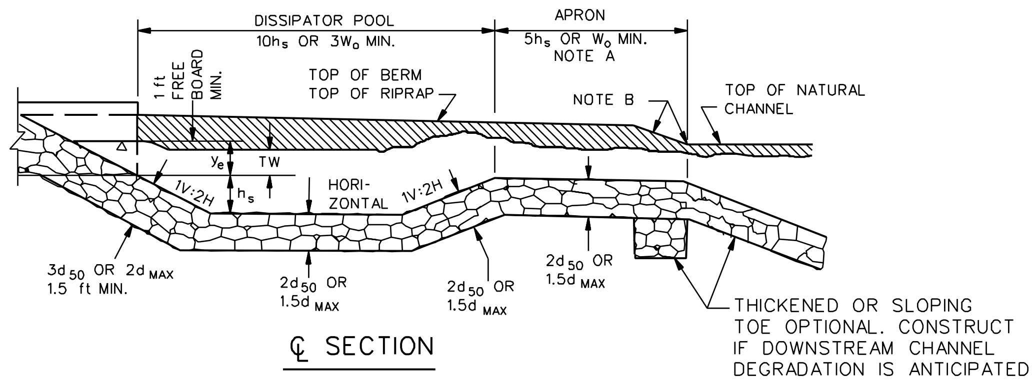
<tr><td colspan="2">OUTLET VELOCITY = 28.24 ft/s</td><td colspan="2">NORMAL VELOCITY = 17.51 ft/s</td></tr>
<tr><td colspan="2">OUTLET DEPTH = 2.02 ft</td><td colspan="2"></td></tr>
<tr><td colspan="4">ST. ANTHONY FALLS BASIN — FINAL DESIGN</td></tr>
<tr><td colspan="4">LB = 13.620 ft LS = 13.031 ft LT = 17.440 ft<br>L = 44.091 ft Y1 = 1.532 ft Y2 = 9.312 ft<br>Z1 = 163.780 ft Z2 = 163.780 ft Z3 = 170.295 ft<br>WB = 7.000 ft WB3 = 7.000 ft<br>— CHUTE BLOCKS —<br>H1 = 1.532 W1 = 1.167 ft W2 = 1.167 ft NC = 3.000<br>— BAFFLE BLOCKS —<br>W3 = 1.167 ft W4 = 1.167 ft NB = 3.000<br>H3 = 1.532 ft LCB = 4.540 ft<br>END SILL<br>H4 = 0.753 ft<br>BASIN OUTLET VELOCITY = 17.510 ft/s</td></tr>
</table>




NOTE A - IF EXIT VELOCITY OF BASIN IS SPECIFIED, EXTEND BASIN AS REQURIED TO OBTAIN SUFFICIENT CROSS SECTIONAL AREA AT SECTION A-A SUCH THAT $Q_{des}$/(CROSS SECTION AREA AT SEC. A-A) = SPECIFIED EXIT VELOCITY.

NOTE B - WARP BASIN TO CONFORM TO NATURAL STREAM CHANNEL. TOP OF RIPRAP IN FLOOR OF BASIN SHOULD BE AT THE SAME ELEVATION OR LOWER THAN NATURAL CHANNEL BOTTOM AT SEC. A-A.

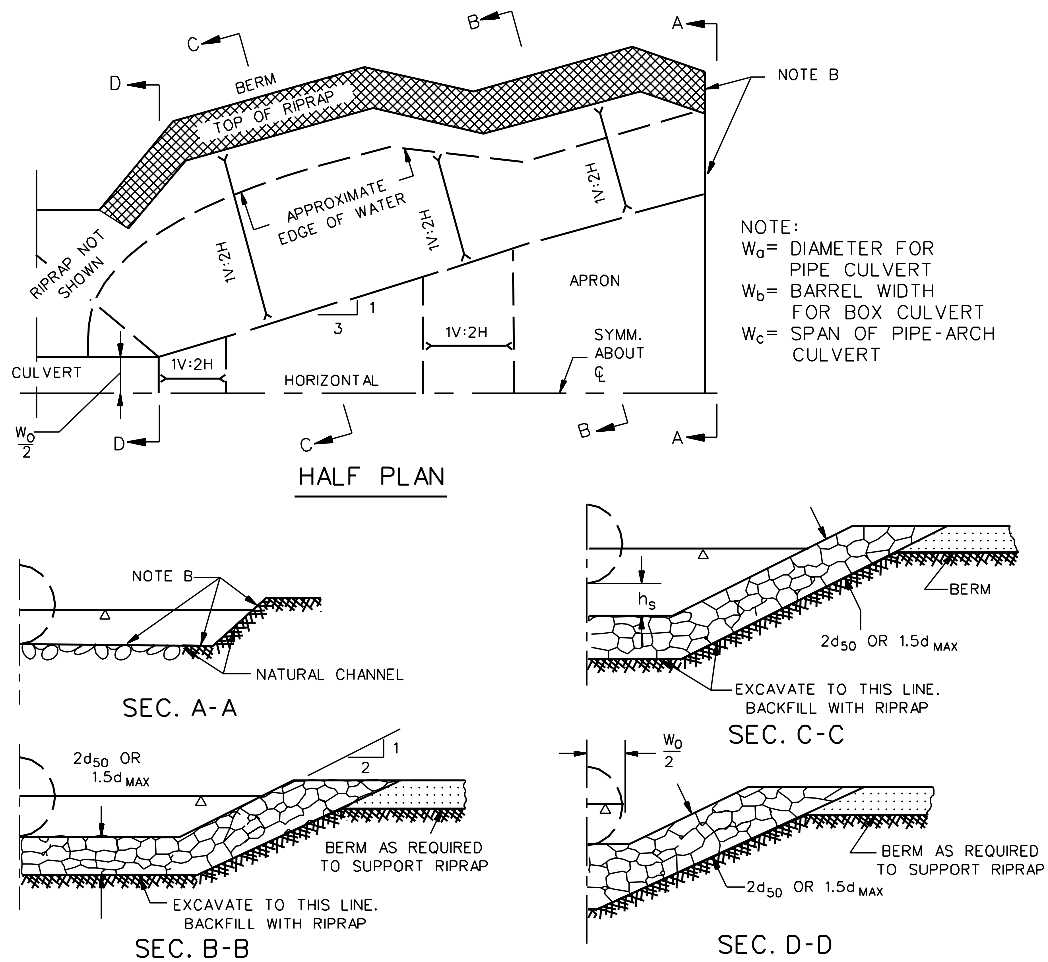



**FIGURE 11-5 — Details Of Riprap Basin Energy Dissipator**

Low Tailwater ($TW/d_o < 0.75$)

- The high-velocity jet of water emerging from the culvert will drop into the preformed scour hole and will be substantially reduced.

- Riprap may be required for the channel downstream of the rock-lined basin.

High Tailwater ($TW/d_o > 0.75$)

- The high-velocity core of water emerging from the culvert retains its jetlike character as it passes through the basin.

- The scour hole is not as deep as with low tailwater and is generally longer.

- Riprap may be required for the channel downstream of the rock-lined basin.

### 11.8.2 Design Procedure

Step 1 Determine Input Flow

a. $d_o$ or $d_E$, $V_o$, Fr at the culvert outlet
($d_E$ = the equivalent depth at the brink = $(A/2)^{0.5}$ ).

Step 2 Check TW

a. If $TW/d_o < 0.75$, TW does not affect design; go to Step 3 and skip Step 6.

b. If $TW/d_o > 0.75$, TW effect must be considered; include Step 6.

Step 3 Determine ($d_{50}$)

a. Use Figure 11-6.
b. Select $d_{50}/d_E$. Satisfactory results will be obtained, if $0.25 < d_{50}/d_E < 0.45$.
c. Obtain $h_S/d_E$ using Froude number, Fr, and Figure 11-6.
d. Check if $2 < h_S/d_{50} < 4$, and repeat until a $d_{50}$ is found within the range.

Step 4 Size Basin

a. As shown in Figure 11-5.
b. Determine length of the dissipating pool, $L_S$:

$L_S = 10h_S$ or $3W_o$ minimum.

c. Determine length of basin, $L_B$:

$L_B = 15h_S$ or $4W_o$ minimum.

d. Thickness of riprap: Approach $= 3d_{50}$ or $1.5\ d_{max}$
Remainder $= 2d_{50}$ or $1.5\ d_{max}$

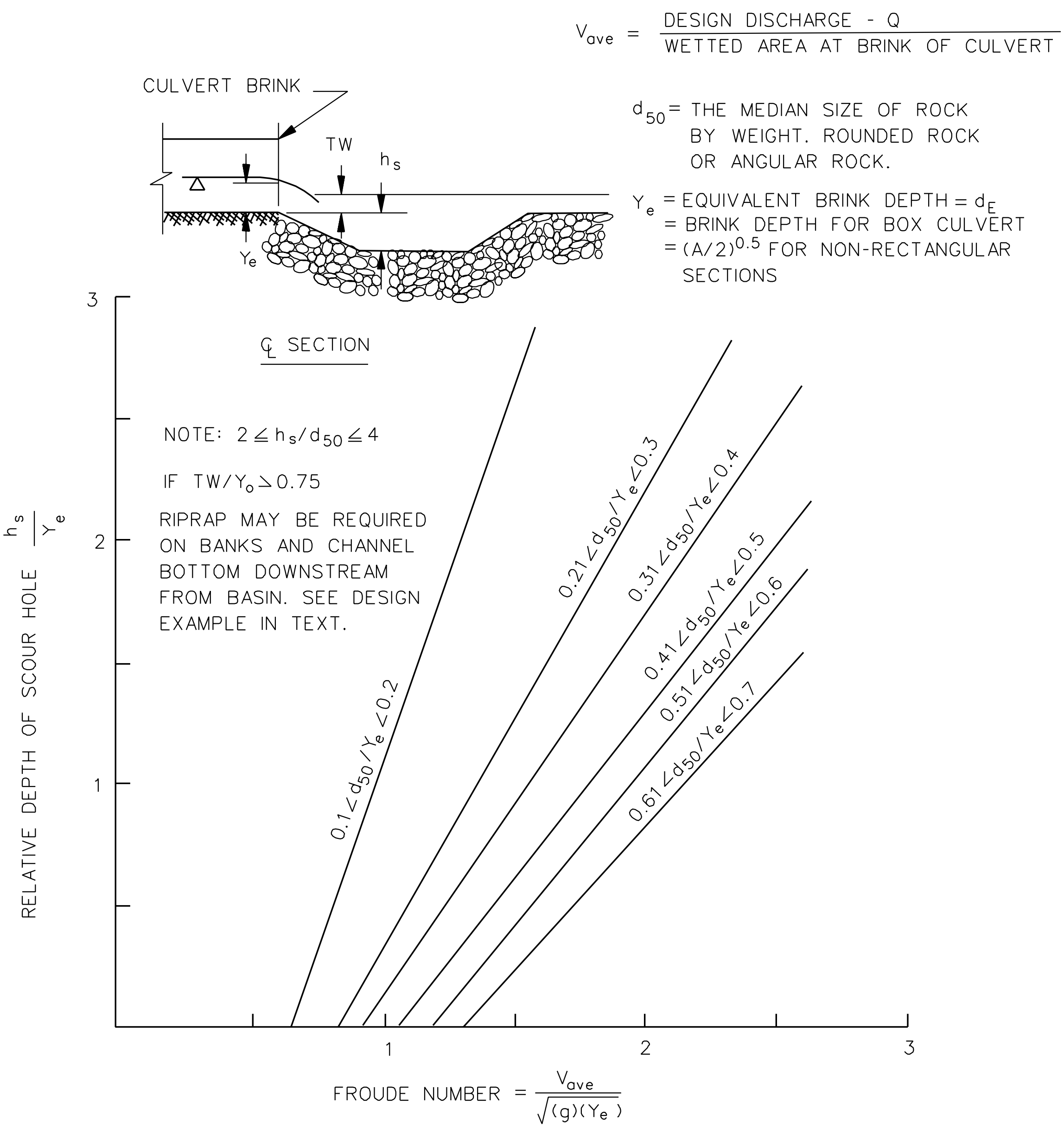


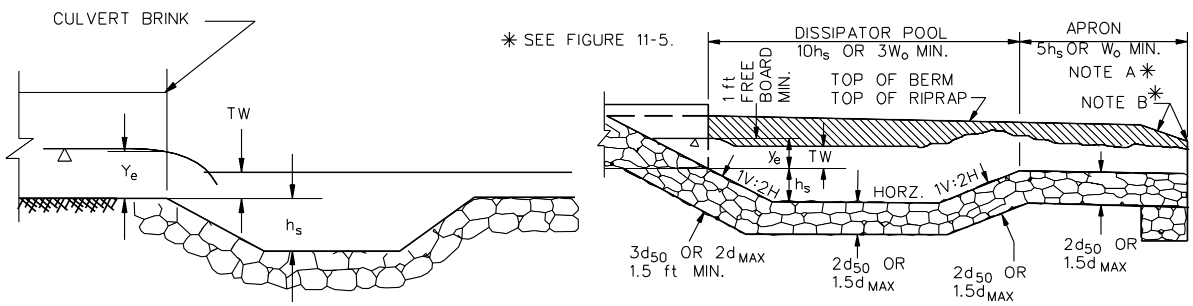

**FIGURE 11-6 — Riprap Basin Depth of Scour**

## RIPRAP BASIN

Project No. ______________________________

Designer ______________________________ Date __________

Reviewer ______________________________ Date __________




| DESIGN VALUES (Figure 11-6) | TRIAL 1 | FINAL TRIAL |
|---|---|---|
| Equivalent Depth, $d_E$ | | |
| $D_{50}/d_E$ | | |
| $D_{50}$ | | |
| Froude No., Fr | | |
| $h_S/d_E$ | | |
| $h_S$ | | |
| $h_S/D_{50}$ | | |
| $2 < h_S/D_{50} < 4$ | | |

| BASIN DIMENSIONS | | FEET | |
|---|---|---|---|
| Pool length is the larger of: | $10h_S$ | | |
| | $3W_o$ | | |
| Basin length is the larger of: | $15h_S$ | | |
| | $4W_o$ | | |
| Approach Thickness | $3D_{50}$ | | |
| Basin Thickness | $2D_{50}$ | | |

| TAILWATER CHECK | |
|---|---|
| Tailwater, TW | |
| Equivalent depth, $d_E$ | |
| $TW/d_E$ | |
| If $TW/d_E > 0.75$, calculate riprap downstream using Figure 11-8 | |
| $D_E = (4A_c/\pi)^{0.5}$ | |

| DOWNSTREAM RIPRAP (Figure 11-8) | | | | |
|---|---|---|---|---|
| $L/D_E$ | L | $V_L/V_o$ | $V_L$ | $D_{50}$ |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

*Note:* "$D_E$," equivalent diameter, is not equal to "$d_E$" or "$Y_E$."

**FIGURE 11-7 — Riprap Basin Design Checklist**

Step 5 Determine ($V_B$)

a. Basin exit depth, $d_B$ = critical depth at basin exit.

b. Basin exit velocity, $V_B = Q/(W_B)(d_B)$.

c. Compare $V_B$ with the average normal flow velocity in the natural channel, $V_d$. The goal of this comparison is that $V_B$ will be the same or lower than the natural channel velocity.

d. If $TW/d_o \leq 0.75$, go to Step 7.

Step 6 High Tailwater Design

a. Design a basin for low tailwater conditions, Steps 1 through 5.

b. Compute equivalent circular diameter $D_E$ for brink area from:

$A = \pi D_E^2/4 = d_o(W_o)$

c. Estimate centerline velocity at a series of downstream cross sections using Figure 11-8.

d. Size riprap using HEC 11 *(9)* or the Channels Chapter.

Step 7 Design Filter

a. Unless the streambed material is sufficiently well graded.
b. Follow instructions in Section 4.4, HEC 11.

### 11.8.3 Design Example — Low Tailwater

Low Tailwater

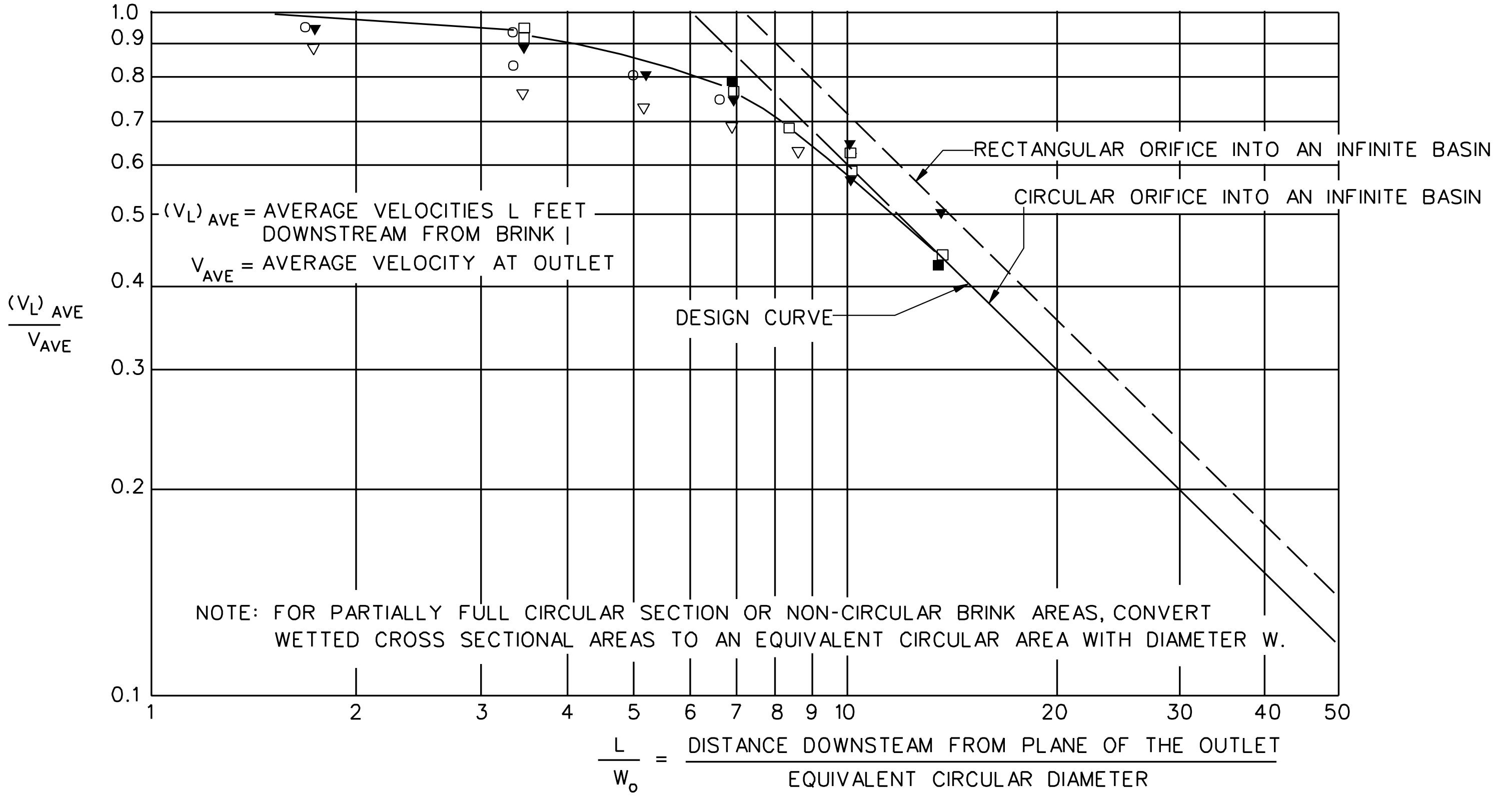
- Box culvert — 8 ft × 6 ft
- Design discharge, $Q = 800\ ft^3/s$
- Supercritical flow in culvert
- Normal flow depth, $d_o$ = brink depth ($d_E$ = 4.00 ft)
- Tailwater depth, TW = 2.80 ft

Step 1 Determine Input Flow

a. $d_o = d_E$ for rectangular section
$d_o = d_E = 4.00$ ft
$V_o = Q/A = 800/(4.00)(8) = 25.00$ ft/s
$Fr = V/(gd_E)^{0.5} = 25.00/[(32.2)(4.00)]^{0.5} = 2.20 < 3.0$, O.K.

Step 2 Check TW

a. Determine if $TW/d_o \leq 0.75$
$TW/d_E = 2.80/4.00 = 0.7$




| SYM | $W_o$ (ft) | Q ($ft^3/s$) | $V_{AVE}$ (ft/s) | TW (ft) |
|---|---|---|---|---|
| □ | 1.44 | 23 | 15.09 | 1.61 |
| □ | 1.44 | 14 | 10.30 | 1.61 |
| ○ | 3.08 | 65 | 9.29 | 3.08 |
| ● | 3.08 | 84 | 11.91 | 3.08 |
| ▽ | 1.44 | 21 | 14.01 | 1.25 |
| ▽ | 1.44 | 14 | 9.29 | 1.25 |

*Note: To be used for predicting channel velocities downstream from culvert outlets where high tailwater prevails. Velocities obtained from the use of this Figure can be used with HEC 11 (9) for sizing riprap.*

**FIGURE 11-8 — Distribution of Centerline Velocity for Flow from Submerged Outlets (after *(17)*)**

Therefore, $TW/d_E < 0.75$, O.K.

Step 3 Determine ($d_{50}$)

a. Use Figure 11-6.
b. Select $d_{50}/d_E = 0.45$: $d_{50} = 0.45(4.00) = 1.80$ ft
c. Obtain $h_S/d_E$ using Fr = 2.2 and line $0.41 \leq d_{50}/d_E \leq 0.5$:

$h_S/d_E = 1.6$

d. Check if $2 < h_S/d_{50} < 4$:
$h_S = 4.00(1.6) = 6.40$ ft
$h_S/d_{50} = 6.40/1.80 = 3.55$ ft
$2 < 3.55 < 4$, O.K.

Step 4 Size Basin

a. As shown in Figure 11-5
b. Determine length of dissipating pool, $L_S$:

$L_S = 10h_S = 10(6.40) = 64.00$ ft
min $= 3W_o = 3(8.00) = 24.00$ ft
Therefore, use $L_S = 64.00$ ft

c. Determine length of basin, $L_B$:

$L_B = 15h_S = 15(6.40) = 96.00$ ft
min $= 4W_o = 4(8.00) = 32.00$ ft
Therefore, use $L_B = 96.00$ ft

d. Thickness of riprap:

Approach $= 3d_{50} = 3(1.80) = 5.40$ ft
Remainder $= 2d_{50} = 2(1.80) = 3.60$ ft

Step 5 Determine ($V_B$)

a. $d_B$ = critical depth at basin exit = 3.30 ft (Assuming a rectangular cross section with width $W_B = 24$ ft
b. $V_B = Q/(W_B d_B) = 800/((2.4)(3.30)) = 10.10$ ft/s
c. $V_B = 10.10$ ft/s $< V_d = 18$ ft/s

### 11.8.4 Design Example — High Tailwater

- Data on the channel and the culvert are the same as above, except that the new tailwater depth, TW = 4.20 ft.
- $TW/d_o = 4.20/4.00 = 1.05 > 0.75$
- Downstream channel can tolerate only 7 ft/s.

Steps 1 through 5 are the same as above.

Step 6 High Tailwater Design

a. Design a basin for low tailwater conditions, Steps 1 through 5 as above:

$d_{50}$ = 1.80 ft, $h_S$ = 6.40 ft
$L_S$ = 64.00 ft, $L_B$ = 96.00 ft

b. Compute equivalent circular diameter, $D_E$, for brink area from:

$$A = \pi D_E^2/4 = d_o(W_o) = 4.00(8.00) = 32.00\ ft^2$$
$$D_E = [32.00(4)/\pi]^{0.5} = 6.4\ ft$$
$$V_o = 25\ ft/s$$

c. Estimate centerline velocity at a series of downstream cross sections using Figure 11-8:

| $L/D_E$ (1) | L | $V_L/V_o$ | $V_L$ | $d_{50}$ (2) |
|---|---|---|---|---|
| 1.0 | 64 | 0.59 | 14.75 | 1.4 |
| 15 (3) | 96 | 0.37 | 9.25 | 0.6 |
| 20 | 128 | 0.30 | 7.50 | 0.4 |
| 21 | 135 | 0.28 | 7.00 | 0.4 |

(1) Use $W_o = D_E$ in Figure 11-8.
(2) From Figure 11-9.
(3) Is on a logarithmic scale, so interpolations must be logarithmically.

d. Size riprap using HEC 11 *(9)*. The channel can be lined with the same size rock used for the basin. Protection must extend at least 135 ft downstream.

### 11.8.5 Computer Output

The dissipator geometry can be computed using the "Energy Dissipator" module, which is available in microcomputer program HY-8, Culvert Analysis (Reference *(12)*). The output of the culvert and channel input data, and computed geometry using this module, are shown after Figure 11-10.

## 11.9 IMPACT BASIN USBR TYPE VI

### 11.9.1 Overview

The USBR Type VI basin, Figure 11-11, was developed by the US Bureau of Reclamation (USBR) *(3)* and:

- is referred to as the USBR Type VI basin or hanging baffle;
- is contained in a relatively small, box-like structure;
- requires no tailwater for successful performance;
- may be used in open channels as well; and
- is not recommended where debris or ice buildup may cause substantial clogging.

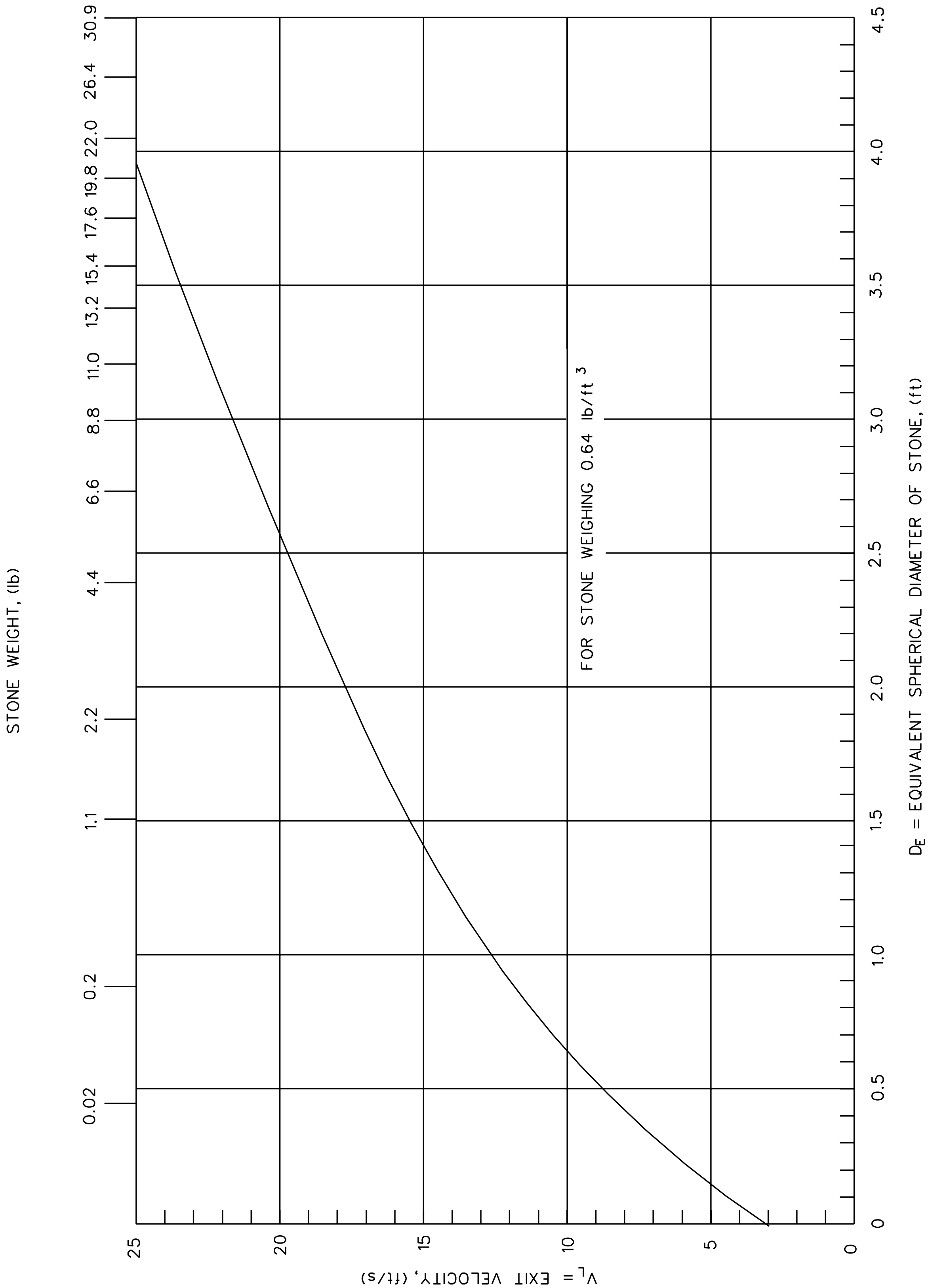
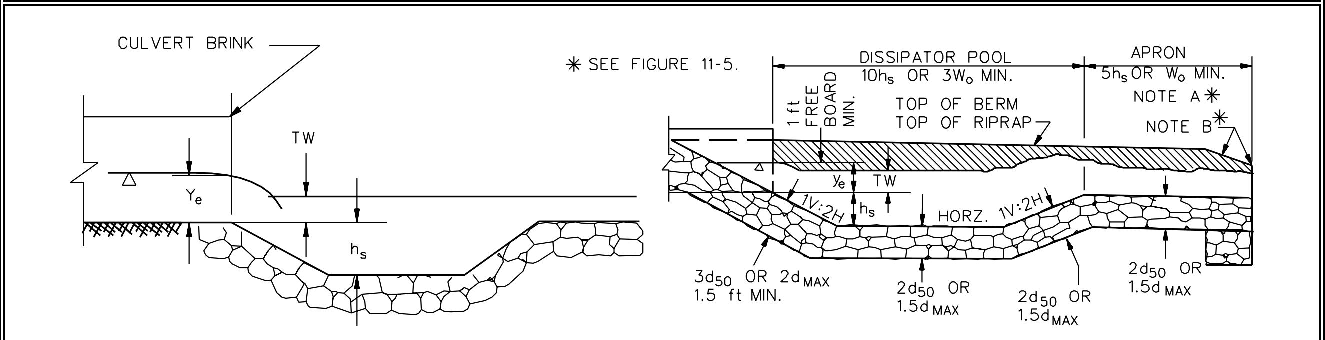



**FIGURE 11-9 — Riprap Size Versus Exit Velocity (after HEC 14 *(11)*)**

RIPRAP BASIN

Project No. Example 11.8.4 (High Tailwater) (US Customary)
Designer PLT Date 8-26-88
Reviewer DLP Date 2-26-03




| DESIGN VALUES (Figure 11-6) | TRIAL 1 | FINAL TRIAL |
|---|---|---|
| Equivalent Depth, $d_E$ | 4.00 ft | 4.00 ft |
| $D_{50}/d_E$ | 0.45 | 0.45 |
| $D_{50}$ | 1.80 ft | 1.80 ft |
| Froude No., Fr | 2.20 | 2.20 |
| $h_S/d_E$ | 1.60 | 1.60 |
| $h_S$ | 6.40 ft | 6.40 ft |
| $h_S/D_{50}$ | 3.55 ft | 3.55 ft |
| $2 < h_S/D_{50} < 4$ | OK | |

| BASIN DIMENSIONS | | METERS | |
|---|---|---|---|
| Pool length is the larger of: | $10h_S$ | 64.00 | 64.00 |
| | $3W_o$ | 24.00 | |
| Basin length is the larger of: | $15h_S$ | 96.00 | 96.00 |
| | $4W_o$ | 32.00 | |
| Approach Thickness | $3D_{50}$ | 5.40 | |
| Basin Thickness | $2D_{50}$ | 3.60 | |

| TAILWATER CHECK | |
|---|---|
| Tailwater, TW | 4.20 ft |
| Equivalent depth, $d_E$ | 4.00 ft |
| $TW/d_E$ | 1.05 |
| If $TW/d_E > 0.75$, calculate riprap downstream using Figure 11-8 | |
| $D_E = (4A_c/\pi)^{0.5}$ | |

| DOWNSTREAM RIPRAP (Figure 11-8) | | | | |
|---|---|---|---|---|
| $L/D_E$ | L | $V_L/V_o$ | $V_L$ | $D_{50}$ |
| 10 | 64 | 0.59 | 14.75 | 1.4 |
| 15 | 96 | 0.37 | 9.25 | 0.6 |
| 20 | 128 | 0.30 | 7.50 | 0.4 |
| 21 | 135 | 0.28 | 7.00 | 0.4 |
| | | | | |

*Note:* "$D_E$," equivalent diameter, is not equal to "$d_E$" or "$Y_E$."

**FIGURE 11-10 — Riprap Basin Design Example**

| FHWA CULVERT ANALYSIS, HY-8, VERSION 6.1 (HY8Energy) | | | |
|---|---|---|---|
| CURRENT DATE<br>02-26-03 | CURRENT TIME<br>15:23:59 | FILE NAME<br>CULEX2 | FILE DATE<br>02-26-03 |
| CULVERT AND CHANNEL DATA | | | |
| CULVERT NO. 1 | | DOWNSTREAM CHANNEL | |
| CULVERT TYPE: 8.00 ft × 6.00 ft | | BOX CHANNEL TYPE: IRREGULAR | |
| CULVERT LENGTH = 300.37 ft | | BOTTOM WIDTH = 5.00 ft | |
| NO. OF BARRELS = 1.0 | | TAILWATER DEPTH = 3.720 ft | |
| FLOW PER BARREL = 800 $ft^3/s$ | | TOTAL DESIGN FLOW = 800 $ft^3/s$ | |
| INVERT ELEVATION = 172.50 ft | | BOTTOM ELEVATION = 172.50 ft | |
| OUTLET VELOCITY = 32.26 ft | | NORMAL VELOCITY = 21.83 ft/s | |
| OUTLET DEPTH = 3.10 ft | | | |

| RIPRAP STILLING BASN — FINAL DESIGN | |
|---|---|
| Basin Length (LB) | 105.778 ft |
| Pool Length (LP) | 70.519 ft |
| Apron Length (LA) | 35.259 ft |
| TB | 8.100 ft |
| TA | 10.800 ft |
| HS | 7.052 ft |
| L 10 | 56.2 ft |
| L 15 | 84.3 ft |
| L 20 | 112.4 ft |
| L 25 | 118.0 ft |
| VL/Vo 10 | 0.59 |
| VL/Vo 15 | 0.39 |
| VL/Vo 20 | 0.30 |
| VL/Vo 25 | 0.24 |
| VL 10 | 18.95 ft/s |
| VL 15 | 12.68 ft/s |
| VL 20 | 9.56 ft/s |
| VL 25 | 7.68 ft/s |
| Rock size D50 10 | 2.32 ft |
| Rock size D50 15 | 1.03 ft |
| Rock size D50 20 | 0.57 ft |
| Rock size D50 25 | 0.35 ft |
| Hs/D50 | 3.771 |

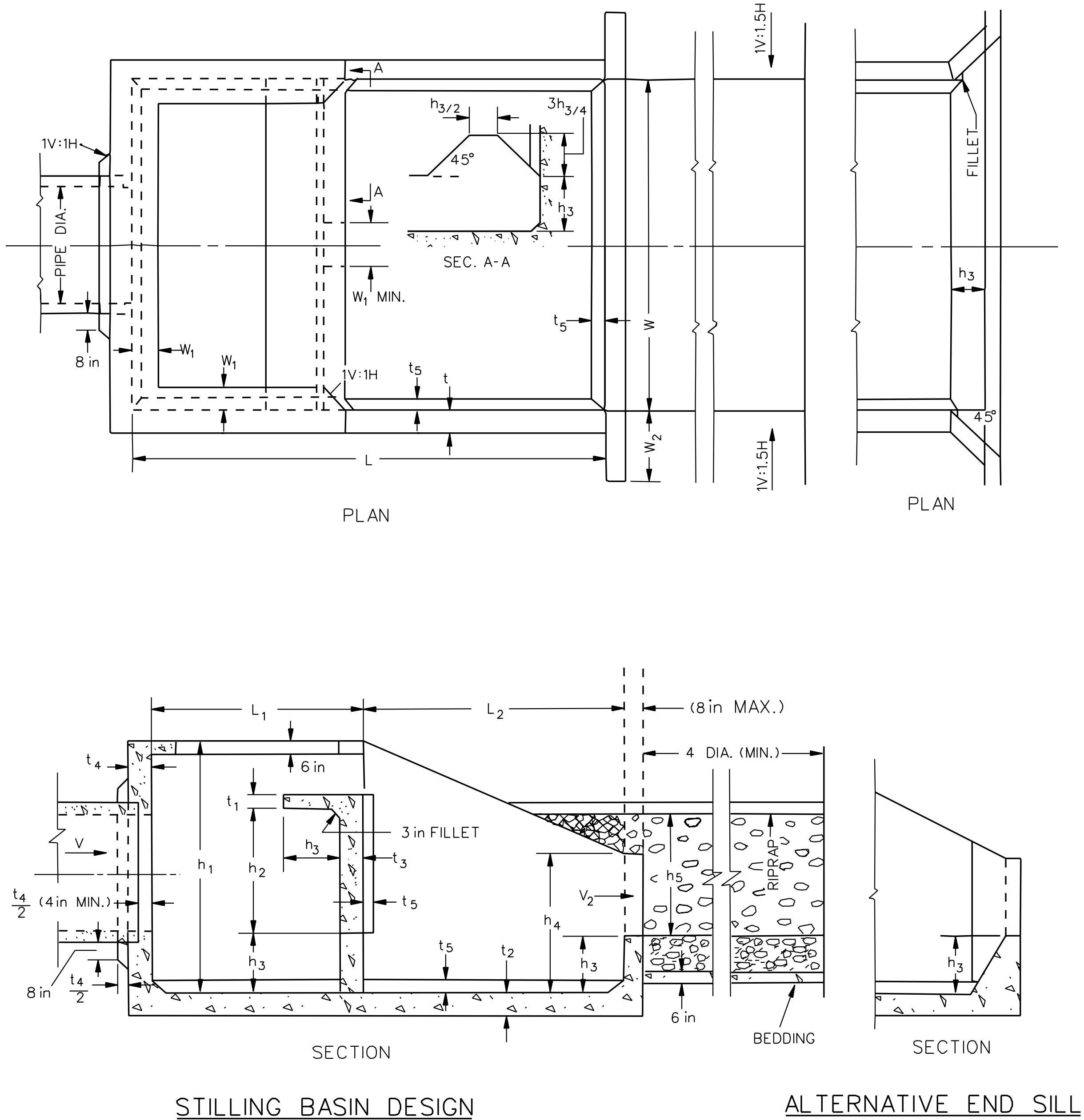


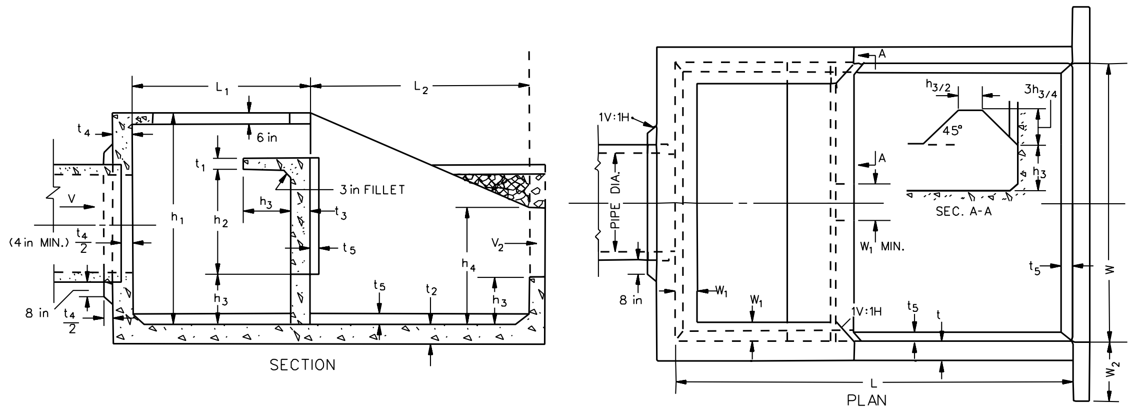

**FIGURE 11-11 — USBR Type VI (Impact) Dissipator**

## USBR TYPE VI BASIN

Project No. ______________________________

Designer ______________________________ Date __________

Reviewer ______________________________ Date __________




| CHOOSE BASIN WIDTH, W (Figure 11-14) | TRIAL 1 | FINAL TRIAL |
|---|---|---|
| Equivalent Depth, $d_E$ | | |
| $V_o$ (ft/s) | | |
| $H_o = d_E + V_o^2/2g$ | | |
| Froude No., Fr | | |
| $H_o/W$ | | |
| $W = H_o/(H_o/W)$ | | |

| CHECK OUTLET VELOCITY, $V_o$ | | | |
|---|---|---|---|
| $H_L/H_o$ (Figure 11-13) | | | |
| $H_L = (H_L/H_o)H_o$ | | | |
| $H_e = H_o - H_L$ | | | |
| $d_B$ | | | |
| $V_B = (Q/W)/d_B$ | | | |
| $(H_e)_T = d_B + V_B^2/2g$ | | | |

| BASIN DIMENSIONS (FEET) FROM TABLE 11-4 | | | | | | | |
|---|---|---|---|---|---|---|---|
| W | $h_1$ | $h_2$ | $h_3$ | $h_4$ | L | $L_1$ | $L_2$ |
| | | | | | | | |
| W | $W_1$ | $W_2$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| | | | | | | | |

**FIGURE 11-12 — Impact Basin Type VI Checklist**

Hanging Baffle

Energy dissipation is initiated by flow striking the vertical hanging baffle and being deflected upstream by the horizontal portion of the baffle and by the floor, creating horizontal eddies.

Notches in Baffle

Notches are provided to aid in cleaning the basin. The notches provide concentrated jets of water for cleaning. The basin is designed to carry the full discharge over the top of the baffle if the space beneath the baffle becomes completely clogged.

Equivalent Depth

This depth must be calculated for a pipe or irregular-shaped conduit. The cross section flow area in the pipe is converted into an equivalent rectangular cross section in which the width is twice the depth of flow.

Limitations

Discharges up to 400 $ft^3/s$ per barrel and velocities as high as 50 ft/s can be used without subjecting the structure to cavitation damage.

Tailwater

A moderate depth of tailwater will improve performance. For best performance, set the basin so that maximum tailwater does not exceed $h_3 + (h_2/2)$.

Slope

If culvert slope is greater than 15°, a horizontal section of at least four culvert widths should be provided upstream.

End Treatment

An end sill with a low-flow drainage slot, 45° wingwalls and a cutoff wall should be provided at the end of the basin.

Riprap

Riprap should be placed downstream of the basin for a length of at least four conduit widths.

### 11.9.2 Design Procedures

Step 1 Calculate Equivalent Depth ($d_E$)

a. Rectangular section, $d_E = d_o = y_o$
b. Other sections, $d_E = (A/2)^{0.5}$

Step 2 Determine Input Flow

a. Froude number, $Fr = V_o/(gd_E)^{0.5}$
b. Specific energy, $H_o = d_E + V_o^2/2g$

Step 3 Determine Basin Width (W)

a. Use Figure 11-14
b. Enter with Fr and read $H_o/W$
c. $W = H_o/(H_o/W)$

Step 4 Size Basin

a. Use Table 11-4 and W
b. Obtain the remaining dimensions

Step 5 Energy Loss

a. Use Figure 11-13
b. Enter with Fr and read $H_L/H_o$
c. $H_L = (H_L/H_o)H_o$

Step 6 Exit Velocity ($V_B$)

a. Exit energy ($H_E$) = $H_o - H_L$

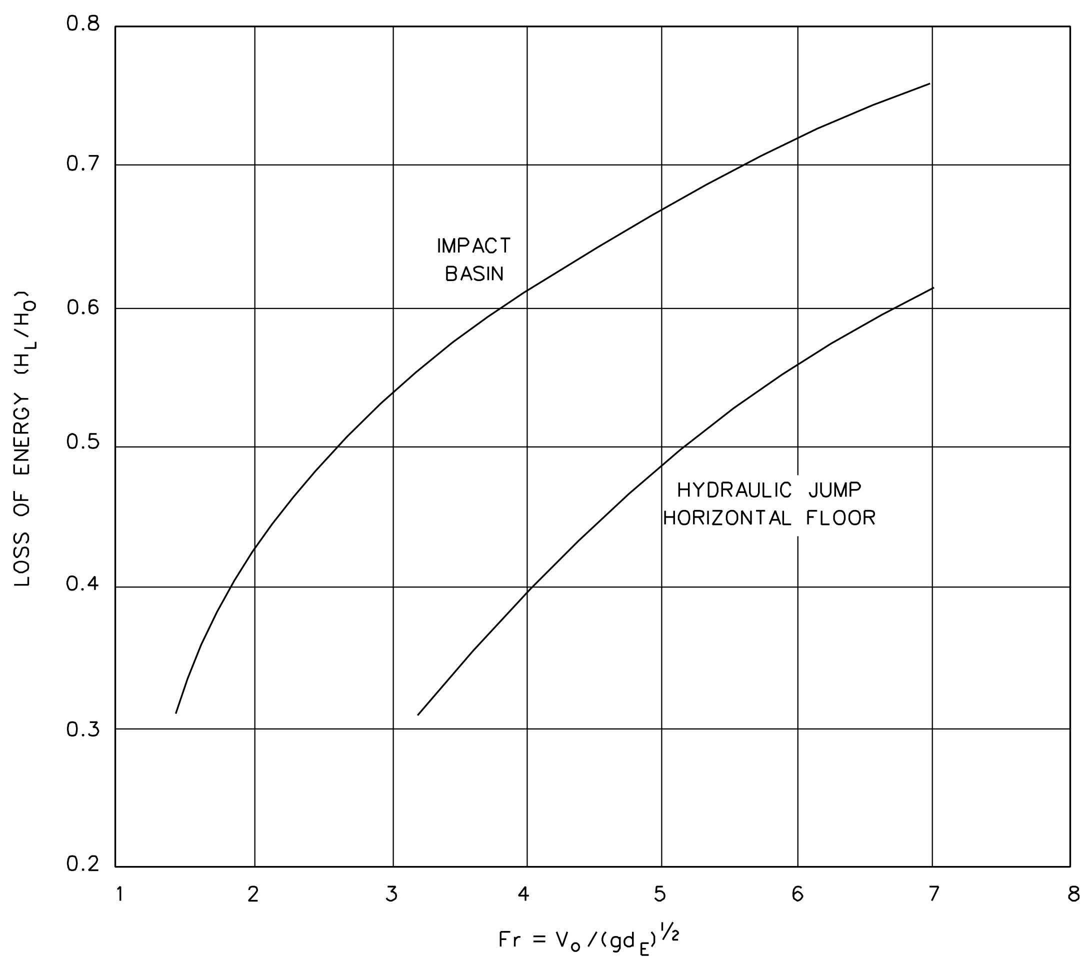



**FIGURE 11-13 — Energy Loss For USBR Type VI Dissipator**

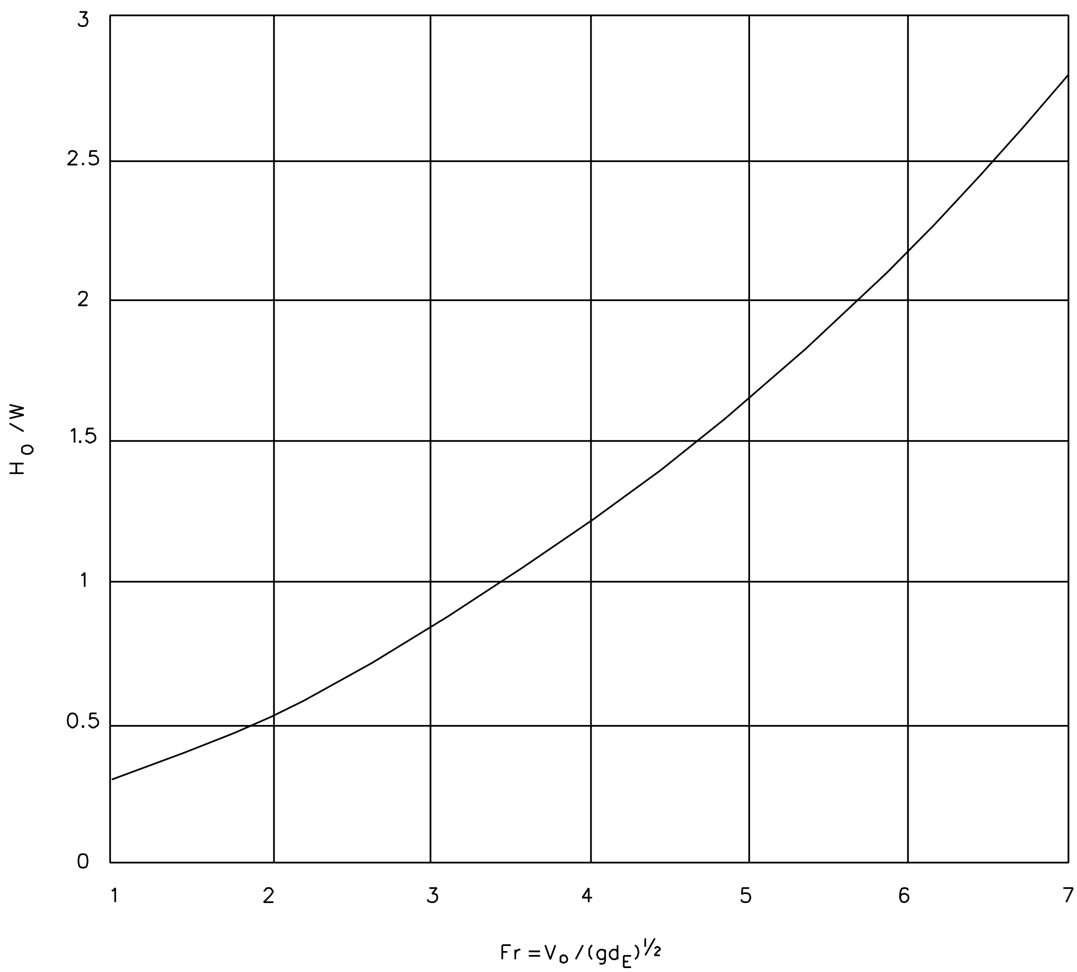



**FIGURE 11-14 — Design Curve For USBR Type VI Dissipator**

b. $H_E = d_B + V_B^2/2g$

$V_B = (Q/W)/d_B$

### 11.9.3 Design Example

Inputs

D = 48 in pipe, $S_o$ = 0.15 ft/ft, n = 0.015
Q = 300 ft$^3$/s, $d_o$ = 2.3 ft, $V_o$ = 40 ft/s

Step 1 Calculate Equivalent Depth ($d_E$)

b. Other sections, $d_E = (A/2)^{0.5}$

A = $Q/V_o$ = 300/40 = 7.5 ft$^2$
$d_E = (7.5/2)^{0.5}$ = 1.94 ft

**TABLE 11-4 — Dimensions of USBR Type VI Basin**

(Dimensions, ft)

(See Figure 11-11)

| W | $h_1$ | $h_2$ | $h_3$ | $h_4$ | L | $L_1$ | $L_2$ |
|---|---|---|---|---|---|---|---|
| 4.00 | 3.08 | 1.50 | 0.67 | 1.67 | 5.42 | 2.33 | 3.08 |
| 5.00 | 3.83 | 1.92 | 0.83 | 2.08 | 6.67 | 2.92 | 3.83 |
| 6.00 | 4.58 | 2.25 | 1.00 | 2.50 | 8.00 | 3.42 | 4.58 |
| 7.00 | 5.42 | 2.58 | 1.17 | 2.92 | 9.42 | 4.00 | 5.42 |
| 8.00 | 6.17 | 3.00 | 1.33 | 3.33 | 10.67 | 4.58 | 6.17 |
| 9.00 | 6.92 | 3.42 | 1.50 | 3.75 | 12.00 | 5.17 | 6.92 |
| 10.00 | 7.58 | 3.75 | 1.67 | 4.17 | 13.42 | 5.75 | 7.67 |
| 11.00 | 8.42 | 4.17 | 1.83 | 4.58 | 14.58 | 6.33 | 8.42 |
| 12.00 | 9.17 | 4.50 | 2.00 | 5.00 | 16.00 | 6.83 | 9.17 |
| 13.00 | 10.17 | 4.92 | 2.17 | 5.42 | 17.33 | 7.42 | 10.00 |
| 14.00 | 10.75 | 5.25 | 2.33 | 5.83 | 18.67 | 8.00 | 10.75 |
| 15.00 | 11.50 | 5.58 | 2.50 | 6.25 | 20.00 | 8.50 | 11.50 |
| 16.00 | 12.25 | 6.00 | 2.67 | 6.67 | 21.33 | 9.08 | 12.25 |
| 17.00 | 13.00 | 6.33 | 2.83 | 7.08 | 21.50 | 9.67 | 13.00 |
| 18.00 | 13.75 | 6.67 | 3.00 | 7.50 | 23.92 | 10.25 | 13.75 |
| 19.00 | 14.58 | 7.08 | 3.17 | 7.92 | 25.33 | 10.83 | 14.58 |
| 20.00 | 15.33 | 7.50 | 3.33 | 8.33 | 26.58 | 11.42 | 15.33 |

| W | $W_1$ | $W_2$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
|---|---|---|---|---|---|---|---|
| 4.00 | 0.33 | 1.08 | 0.50 | 0.50 | 0.50 | 0.50 | 0.25 |
| 5.00 | 0.42 | 1.42 | 0.50 | 0.50 | 0.50 | 0.50 | 0.25 |
| 6.00 | 0.50 | 1.67 | 0.50 | 0.50 | 0.50 | 0.50 | 0.25 |
| 7.00 | 0.50 | 1.92 | 0.50 | 0.50 | 0.50 | 0.50 | 0.25 |
| 8.00 | 0.58 | 2.17 | 0.50 | 0.58 | 0.58 | 0.50 | 0.25 |
| 9.00 | 0.67 | 2.50 | 0.58 | 0.58 | 0.67 | 0.58 | 0.25 |
| 10.00 | 0.75 | 2.75 | 0.67 | 0.67 | 0.75 | 0.67 | 0.25 |
| 11.00 | 0.83 | 3.00 | 0.67 | 0.75 | 0.75 | 0.67 | 0.33 |
| 12.00 | 0.92 | 3.00 | 0.67 | 0.83 | 0.83 | 0.75 | 0.33 |
| 13.00 | 1.00 | 3.00 | 0.67 | 0.92 | 0.83 | 0.83 | 0.33 |
| 14.00 | 1.08 | 3.00 | 0.67 | 1.00 | 0.92 | 0.92 | 0.42 |
| 15.00 | 1.17 | 3.00 | 0.67 | 1.00 | 1.00 | 1.00 | 0.42 |
| 16.00 | 1.25 | 3.00 | 0.75 | 1.00 | 1.00 | 1.00 | 0.50 |
| 17.00 | 1.33 | 3.00 | 0.75 | 1.08 | 1.00 | 1.00 | 0.50 |
| 18.00 | 1.33 | 3.00 | 0.75 | 1.08 | 1.08 | 1.08 | 0.58 |
| 19.00 | 1.42 | 3.00 | 0.83 | 1.17 | 1.08 | 1.08 | 0.58 |
| 20.00 | 1.50 | 3.00 | 0.83 | 1.17 | 1.17 | 1.17 | 0.67 |

Step 2 Determine Input Flow

a. Froude number, $Fr_o = V_o/(gd_E)^{0.5}$:

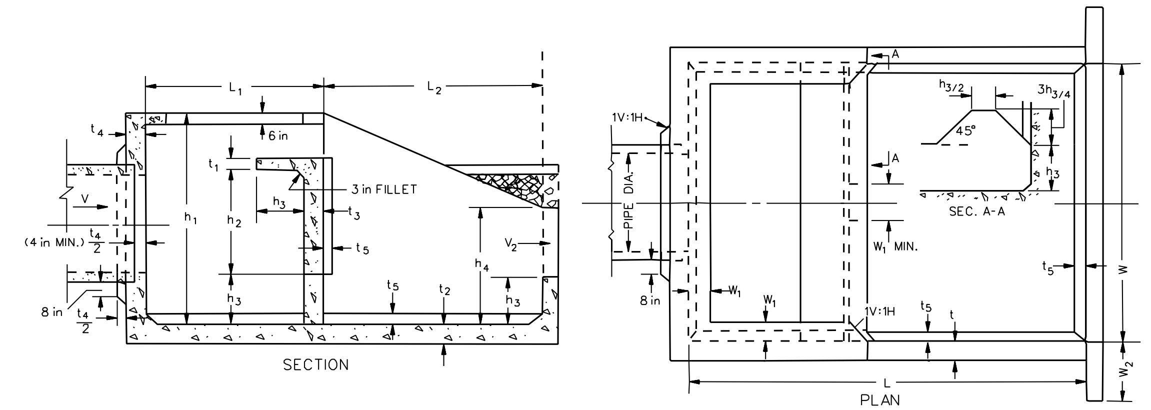
$Fr = 40[32.2(1.94)]^{0.5} = 5.06$

b. Specific energy, $H_o = d_E + V_o^2/2g$:

$H_o = 1.94 + (40)^2/(2)(32.2) = 24.87$ ft

## USBR TYPE VI BASIN

Project No. I-31 (88) over Example Creek
Designer PLT Date 8-26-88
Reviewer DLP Date 2-27-03




| CHOOSE BASIN WIDTH, W (Figure 11-14) | TRIAL 1 | FINAL TRIAL |
|---|---|---|
| Equivalent Depth, $d_E$ | 1.94 | 1.94 |
| $V_o$ (ft/s) | 40.00 | 40.00 |
| $H_o = d_E + V_o^2/2g$ | 24.87 | 24.87 |
| Froude No., Fr | 5.1 | 5.1 |
| $H_o/W$ | 1.68 | 1.68 |
| $W = H_o/(H_o/W)$ | 14.80 | 14.80 |

| CHECK OUTLET VELOCITY, $V_o$ | | | |
|---|---|---|---|
| $H_L/H_o$ (Figure 11-13) | 0.67 | | |
| $H_L = (H_L/H_o)H_o$ | 16.66 | | |
| $H_e = H_o - H_L$ | 8.21 | | |
| $d_B$ | 2.30 | 0.66 | 0.82 |
| $V_B = (Q/W)/d_B$ | 8.20 | 28.71 | 22.97 |
| $(H_e)_T = d_B + V_B^2/2g$ | 3.35 | 13.45 | 9.02 |

BASIN DIMENSIONS (FEET) FROM TABLE 11-4

| W | $h_1$ | $h_2$ | $h_3$ | $h_4$ | L | $L_1$ | $L_2$ |
|---|---|---|---|---|---|---|---|
| 16 | 12.25 | 6.00 | 2.67 | 6.67 | 21.33 | 9.08 | 12.25 |
| W | $W_1$ | $W_2$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| 16 | 1.25 | 3.00 | 0.75 | 1.00 | 1.00 | 1.00 | 0.50 |

**FIGURE 11-15 — USBR Basin Type VI (Design Example)**

Step 3 Determine Basin Width (W)

a. Use Figure 11-14
b. Enter with Fr = 5.06 and read $H_o/W = 1.68$
c. $W = H_o/(H_o/W) = 24.87/1.68 = 14.80$ ft

Step 4 Size Basin

a. Use Table 11-4 and W.
b. Obtain the remaining dimensions.

Step 5 Energy Loss

a. Use Figure 11-13
b. Enter with Fr = 5.06 and read $H_L/H_o = 0.67$
c. $H_L = (H_L/H_o)H_o = 0.67(24.87) = 16.66$ ft

Step 6 Exit Velocity ($V_B$)

a. Exit energy ($H_E$) = $H_o - H_L = 24.87 - 16.66 = 8.21$ ft

b. $H_E = d_B + V_B^2/2g = 8.21\,\text{ft}$

$V_B = (Q/W)/d_B = (300/14.80)/d_B = 20.27/d_B$

| $d_B$ | $V_B$ | $d_B + V_B^2/2g = 8.83$ |
|---|---|---|
| 2.30 = $d_c$ | 8.20 | 3.35 |
| 0.98 | 19.12 | 6.66 |
| 0.66 | 28.71 | 13.45 |
| 0.85 | 22.08 | 8.43 |
| 0.89 | 21.26 | 7.91 |
| 0.82 | 22.97 | 9.02 ≈ 8.83: |

### 11.9.4 Computer Output

The dissipator geometry can be computed using the “Energy Dissipator” module, which is available in microcomputer program HY-8, Culvert Analysis (Reference *(10)*). The output of the culvert and channel input data, and computed geometry using this module, are shown on the next page.

## 11.10 DROP STRUCTURES

### 11.10.1 Background

Check dams or channel drop structures are used downstream of highway crossings to arrest head cutting and maintain a stable streambed elevation in the vicinity of the bridge. Check dams are usually built of rock riprap, concrete, sheet piles, gabions or treated timber piles. The material used to construct the structure depends on the availability of materials, the height of drop required and the width of the channel. Rock riprap and timber pile construction have been most successful on channels having small drops and widths less than 100 ft. Sheet piles, gabions, and concrete structures are generally used for larger drops on channels with widths ranging up to 325 ft. Check dam location with respect to the bridge depends on the hydraulics of the bridge reach and the amount of headcutting or degradation anticipated.

| FHWA CULVERT ANALYSIS, HY-8, VERSION 6.1 (HY8Energy) | | | |
|---|---|---|---|
| CURRENT DATE<br>02-27-03 | CURRENT TIME<br>16:13:53 | FILE NAME<br>CULEX1B8 | FILE DATE<br>02-27-03 |
| CULVERT AND CHANNEL DATA | | | |
| CULVERT NO. 1 | | DOWNSTREAM CHANNEL | |
| CULVERT TYPE: 48 in CIRCULAR | | BOX CHANNEL TYPE: IRREGULAR | |
| CULVERT LENGTH = 300.37 ft | | BOTTOM WIDTH = 5.00 ft | |
| NO. OF BARRELS = 1.0 | | TAILWATER DEPTH = 2.49 ft | |
| FLOW PER BARREL = 300 $ft^3/s$ | | TOTAL DESIGN FLOW = 300 $ft^3/s$ | |
| INVERT ELEVATION = 172.50 ft | | BOTTOM ELEVATION = 172.50 ft | |
| OUTLET VELOCITY = 29.24 ft/s | | NORMAL VELOCITY = 15.94 ft/s | |
| OUTLET DEPTH = 3.05 ft | | | |

| USBR TYPE 6 DISSIPATOR — FINAL DESIGN | | |
|---|---|---|
| BASIN OUTLET VELOCITY = 8.636 ft/s | | |
| W = 15.000 ft | W1 = 1.167 ft | W2 = 3.000 ft |
| L = 20.000 ft | L1 = 8.500 ft | L2 = 11.500 ft |
| H1 = 11.500 ft | H2 = 5.583 ft | H3 = 2.500 ft |
| H4 = 6.250 ft | T1 = 0.667 ft | T2 = 1.000 ft |
| T3 = 1.000 ft | T4 = 1.000 ft | T5 = 0.417 ft |

Check dams can initiate erosion of banks and the channel bed downstream of the structure as a result of energy dissipation and turbulence at the drop. This local scour can undermine the check dam and cause failure. The use of energy dissipators downstream of check dams can reduce the energy available to erode the channel bed and banks. **In some cases, it may be better to construct several consecutive drops of shorter height to minimize erosion.** Concrete-lined basins as discussed later may also be used.

Lateral erosion of channel banks just downstream of drop structures is another adverse result of check dams and is caused by turbulence produced by energy dissipation at the drop, bank slumping from local channel bed erosion or eddy action at the banks. Bank erosion downstream of check dams can lead to erosion of bridge approach embankments and abutment foundations if lateral bank erosion causes the formation of flow channels around the ends of check dams. The usual solution to these problems is to place riprap revetment on the streambank adjacent to the check dam. The design of riprap is given in HDS 6 *(14)*, HEC 11 *(9)* and Design Guideline 12 of Reference *(7)*.

Erosion of the streambed can also be reduced by placing rock riprap in a preformed scour hole downstream of the drop structure. A row of sheet piling with the top set at or below streambed elevation can prevent the riprap from moving downstream. Because of the problems associated with check dams, the design of these countermeasures requires designing the check dams to resist scour by providing for dissipation of excess energy and protection of areas of the bed and the bank that are susceptible to erosive forces.

## 11.10.2 Bed Scour for Vertical Drop Structures

### 11.10.2.1 Estimating Bed Scour

The most conservative estimate of scour downstream of channel drop structures is for vertical drops with unsubmerged flow conditions. For design, the maximum expected scour can be assumed to be equal to the scour for a vertical, unsubmerged drop, regardless of whether the drop is actually sloped or is submerged.

A sketch of a typical vertical drop structure with a free overfall is shown in Figure 11-16. An equation developed by the US Bureau of Reclamation (USBR) (Reference *(15)*) is recommended to estimate the depth of scour downstream of a vertical drop:

$$d_s = K_u H_t^{0.225} q^{0.54} - d_m \qquad (11.12)$$

where:

$d_s$ = local scour depth for a free overfall, measured from the streambed downstream of the drop, ft

$q$ = discharge per unit width, $ft^3/s/ft$

$H_t$ = total drop in head, measured from the upstream to the downstream energy grade line, ft

$d_m, Y_d$ = tailwater depth, ft

$K_u$ = 1.32

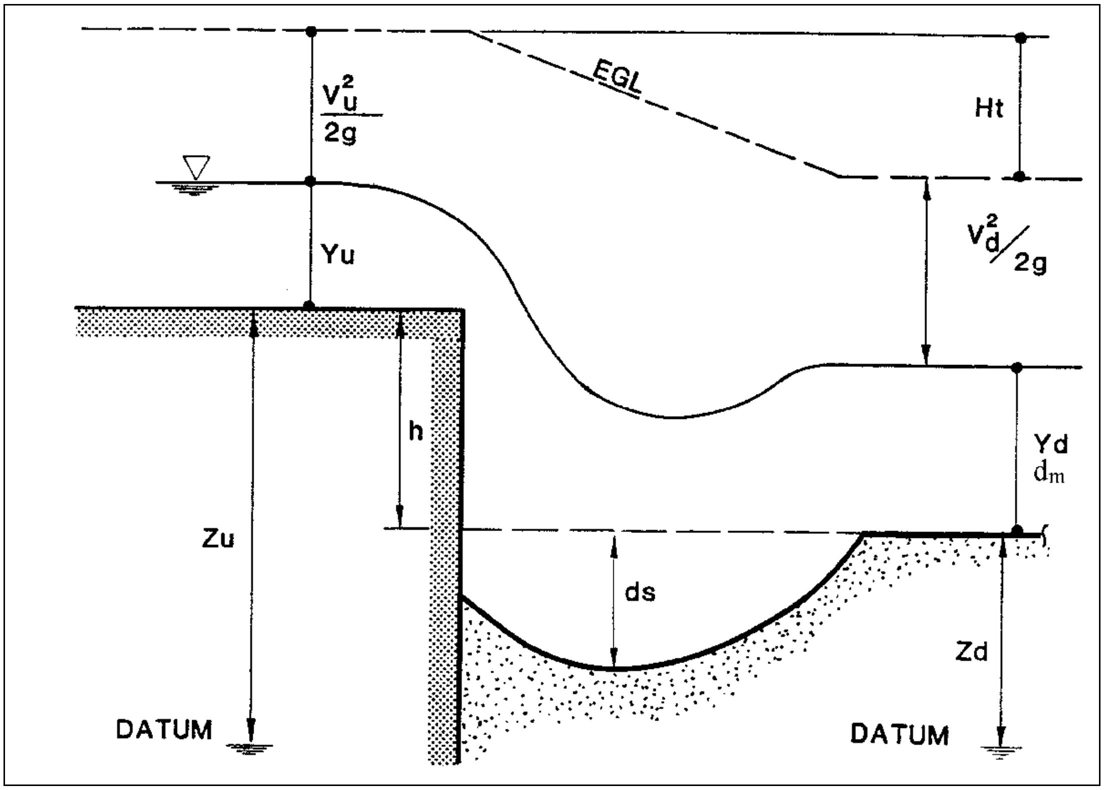



**FIGURE 11-16 — Schematic of a Vertical Drop Caused By a Check Dam**

Note that $H_t$ is the difference in the total head from upstream to downstream. This can be computed using the energy equation for steady uniform flow:

$$H_t = \left( Y_u + \frac{V_u^2}{2g} + Z_u \right) - \left( Y_d + \frac{V_d^2}{2g} + Z_d \right) \tag{11.13}$$

where:
- Y = depth, ft
- V = velocity, ft/s
- Z = bed elevation referenced to a common datum, ft
- G = acceleration due to gravity, 32.2 ft/$s^2$

The subscripts, u and d, refer to upstream and downstream of the channel drop, respectively.

The depth of scour as estimated by Equation 11.13 is independent of the grain size of the bed material. This concept acknowledges that the bed will scour regardless of the type of material composing the bed, but the rate of scour depends on the composition of the bed. In some cases, with large or resistant material, it may take years or decades to develop the maximum scour hole. In these cases, the design life of the bridge may need to be considered when designing the check dam.

**The check dam must be designed structurally to withstand the forces of water and soil assuming that the scour hole is as deep as estimated using Equation 11.13**. Therefore, the designer should consult geotechnical and structural engineers so that the drop structure will be stable under the full-scour condition. In some cases, a series of drops may be employed to minimize drop height and construction costs of foundations. Riprap or energy dissipation could be provided to limit depth of scour (see, for example, Reference *(5)* and HEC 14 *(11)*).

### 11.10.2.2 Check Dam Design Example

The following design example is based upon a comparison of scour equations presented by USBR (Reference *(5)*).

Given:

Channel degradation is threatening bridge foundations. Increasing the bed elevation 4.6 ft will stabilize the channel at the original bed level. A drop structure will raise the channel bed and reduce upstream channel slopes, resulting in greater flow depths and reduced velocity upstream of the structure. For this example, as illustrated by Figure 11-17, the following hydraulic parameters are used:

| | | | |
|---|---|---|---|
| Design Discharge | Q | = | 5,897 $ft^3/s$ |
| Channel Width | B | = | 105 ft |
| Upstream Water Depth | $Y_u$ | = | 10.6 ft |
| Tailwater Depth | $d_m$, $Y_d$ | = | 9.5 ft |
| Unit Discharge | Q | = | 56 $ft^3/s/ft$ |
| Upstream Mean Velocity | $V_u$ | = | 5.3 ft/s |
| Downstream Mean Velocity | $V_d$ | = | 5.9 ft/s |
| Drop Height | H | = | 4.6 ft |

$H_t$ is calculated from the energy equation. Using the downstream bed as the elevation datum gives:

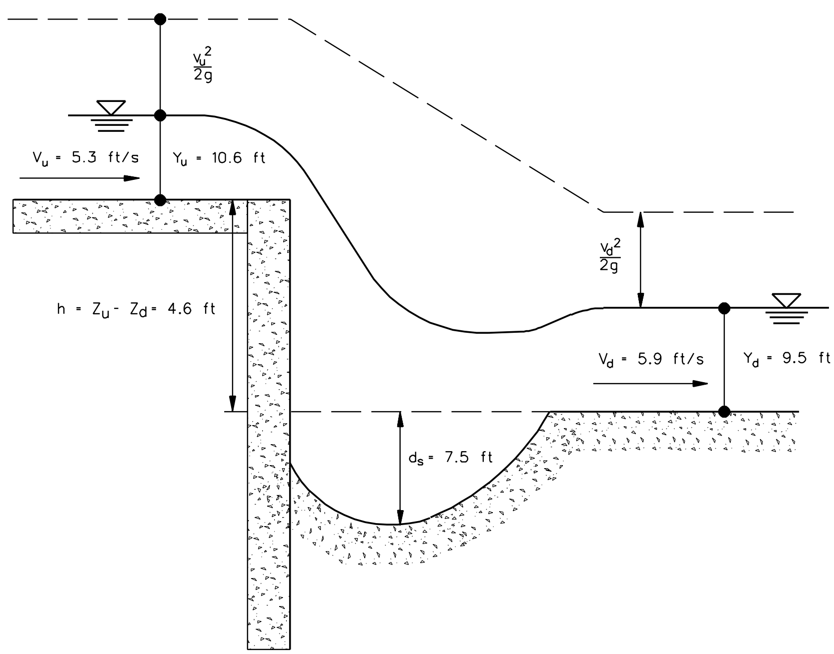



**FIGURE 11-17 — Design Example of Scour Downstream of a Drop Structure**

$$H_t = \left(10.6 + \frac{(5.3)^2}{(2)(32.2)} + 4.6\right) - \left(9.5 + \frac{(5.9)^2}{(2)(32.2)} + 0\right) = 5.6 \text{ ft} \qquad (11.14)$$

Using Equation 11.12, the estimated depth of scour below the downstream bed level is:

$$d_s = K_u H_t^{0.225} q^{0.54} - d_m$$

$$d_s = 1.32(5.6)^{0.225}(56)^{0.54} - 9.5$$

$$d_s = 7.6 \text{ ft}$$

In this case, the unsupported height of the structure is (h + $d_s$) or 12.2 ft. If, for structural reasons, this height is unacceptable, then either riprap to limit scour depth or a series of check dams could be constructed. It should be noted that if a series of drops are required, an adequate distance between each drop must be maintained.

#### 11.10.2.3 Lateral Scour Downstream of Check Dams

As mentioned, lateral scour of the banks of a stream downstream of check dams can cause the streamflow to divert around the check dam. If this occurs, a head cut may move upstream and endanger the highway crossing. To prevent this, the banks of the stream must be adequately protected using riprap or other revetments. Riprap should be sized and placed in a similar fashion as for spurs and guide banks. The designer is referred to HDS 6 *(14)* or HEC 11 *(9)* for proper sizing and placement of riprap on the banks. Revetments are discussed in Design Guideline 12 of Reference *(7)*.

### 11.10.3 <u>Stilling Basins For Drop Structures</u>

This Section on stilling basins for drop structures is taken from HEC 14 *(11)*.

A general design for a stilling basin at the toe of a drop structure was developed by the St. Anthony Falls Hydraulic Laboratory, University of Minnesota. The basin consists of a horizontal apron with blocks and sills to dissipate energy. Tailwater also influences the amount of energy dissipated. The stilling basin length computed for the minimum tailwater level required for good performance may be inadequate at high tailwater levels. Dangerous scour of the downstream channel may occur if the nappe is supported sufficiently by high tailwater so that it lands beyond the end of the stilling basin. A method for computing the stilling basin length for all tailwater levels is presented.

The design is applicable to relative heights of fall ranging from 1.0($h_o/y_c$) to 15($h_o/y_c$) and to crest lengths greater than 1.5$y_c$. Here, $h_o$ is the vertical distance between the crest and the stilling basin floor, and $y_c$ is the critical depth of flow at the crest (see Figure 11-18). The straight drop structure is effective if the drop does not exceed 15 ft and if there is sufficient tailwater.

There are several elements that must be considered in the design of this stilling basin. These include the length of basin, the position and size of floor blocks, the position and height of end sill, the position of the wingwalls and the approach channel geometry. Figure 11-18 illustrates a straight drop structure that provides protection from scour in the downstream channel.

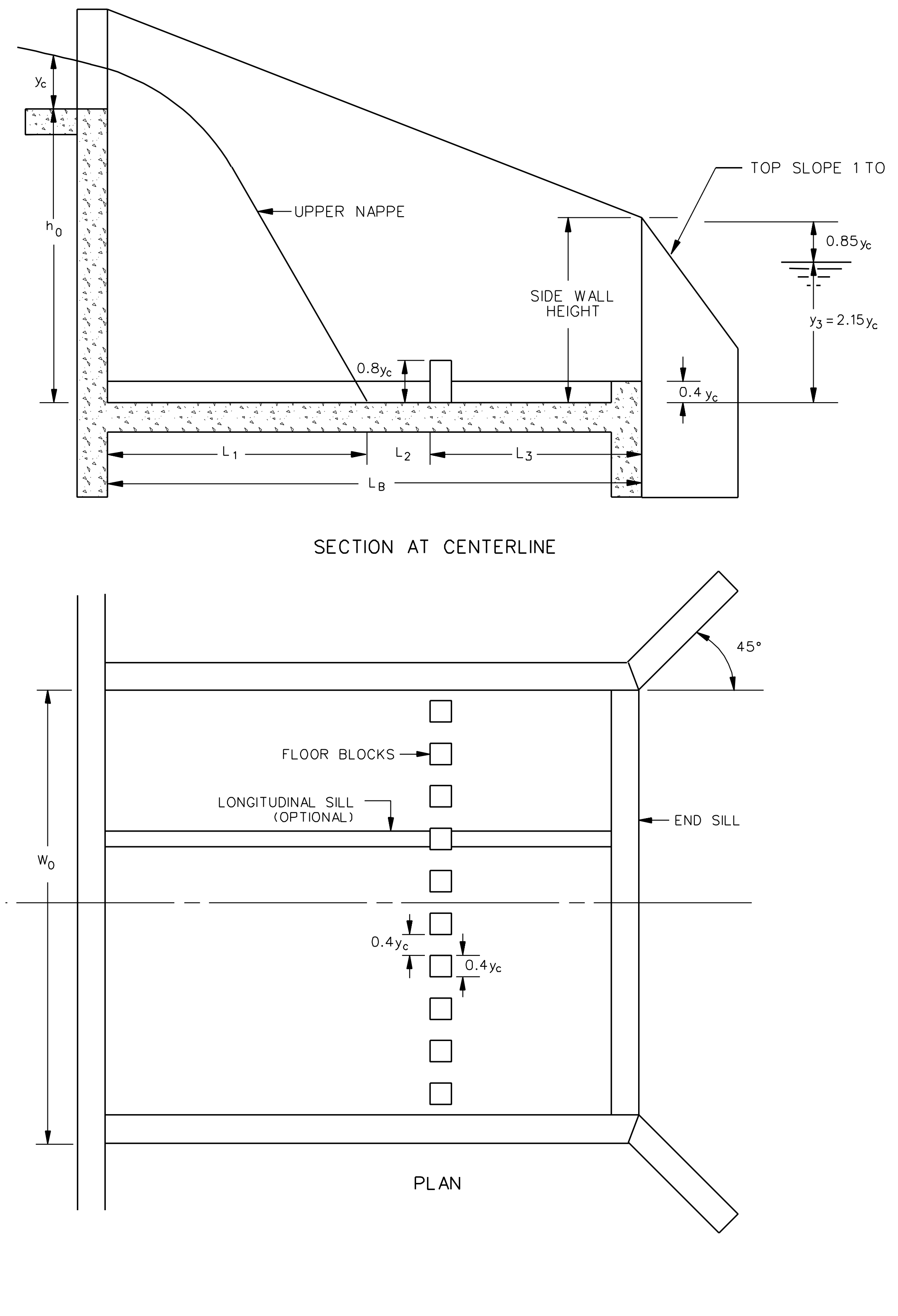



**FIGURE 11-18 — Straight Drop Structure Stilling Basin**

#### 11.10.3.1 Design Procedures

1. Calculate the specific head in approach channel:

$$H = y_o + \frac{V_o^2}{2g} \tag{11.15}$$

where: $y_o$ = normal depth in the approach channel, ft
$V_o$ = velocity associated with normal depth in the approach channel, ft/s

2. Calculate critical depth:

$$y_c = \frac{2}{3}H \tag{11.16}$$

3. Calculate the minimum height for tailwater surface above the floor of the basin:

$$y_3 = 2.15\ y_c \tag{11.17}$$

4. Calculate the vertical distance of tailwater below the crest. This will generally be a negative value because the crest is used as a reference point:

$$h_2 = -(h - y_o) \tag{11.18}$$

where: "h" = total drop from the crest of the drop to the flow line of the outlet channel and $y_o$ is the normal depth in the outlet channel

5. Determine the location of the stilling basin floor relative to the crest:

$$h_o = h_2 - y_3 \tag{11.19}$$

6. Determine the minimum length of the stilling basin, $L_B$, using:

$$L_B = L_1 + L_2 + L_3 = L_1 + 2.25\ y_c \tag{11.20}$$

where:

$L_1$ is the distance from the headwall to the point where the surface of the upper nappe strikes the stilling basin floor. This is given by:

$$L_1 = (L_f + L_s)\ /\ 2 \tag{11.21}$$

where:

$$L_f = y_c \left\{ -0.406 + \sqrt{3.195 - \frac{4.368\ h_o}{y_c}} \right\} \tag{11.22}$$

$$L_t = \left\{ -0.406 + \sqrt{3.195 - \frac{4.368\ h_2}{y_c}} \right\} y_c \tag{11.23}$$

$$L_s = \frac{\left[0.691 + 0.228\left(\frac{L_t}{y_c}\right)^2 - \left(\frac{h_o}{y_c}\right)\right] y_c}{\left[0.185 + 0.456\left(\frac{L_t}{y_c}\right)\right]} \tag{11.24}$$

$L_1$ can be found graphically from Figure11-19.

$L_2$ is the distance from the point at which the surface of the upper nappe strikes the stilling basin floor to the upstream face of the floor blocks; see Figure 11-18. This distance can be determined by:

$$L_2 = 0.8\,(y_c) \tag{11.25}$$

$L_3$ is the distance between the upstream face of the floor blocks and the end of the stilling basin. This distance can be determined from: $L_3 > 1.75\ y_c$ (11.26)

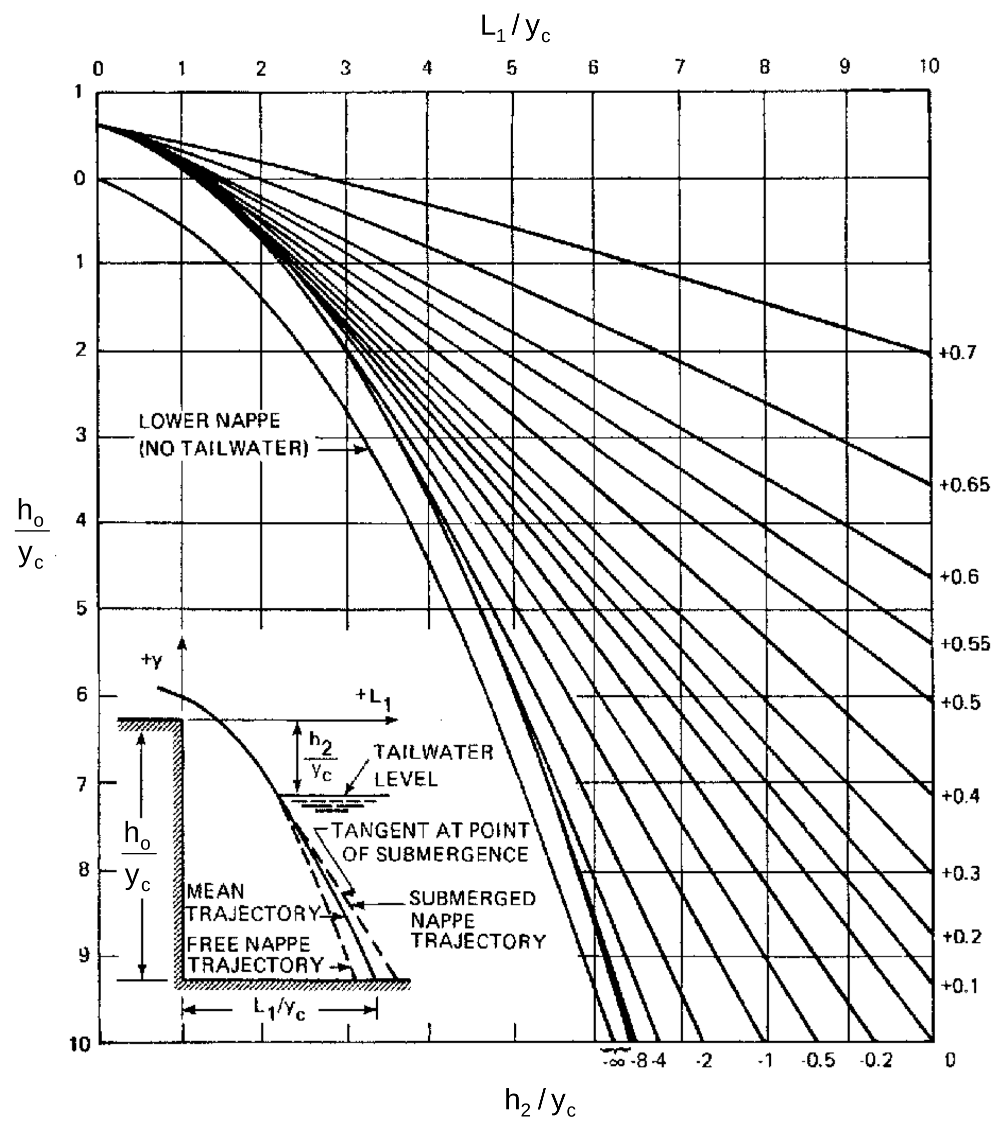



**FIGURE 11-19 — Design Chart for Determination of $L_1$ (after *(6)*)**

7. Proportion the floor blocks as follows:

   a. Height is $0.8y_c$.
   b. Width and spacing should be $0.4y_c$, with a variation of $\pm$ $0.15y_c$, permitted.
   c. Blocks should be square in plan.
   d. Blocks should occupy between 50% and 60% of the stilling basin width.

8. Calculate the end sill height ($0.4y_c$).

9. Longitudinal sills, if used, should pass through, not between, the floor blocks. These sills are for structural purposes and are neither beneficial nor harmful hydraulically.

10. Calculate the sidewall height above the tailwater level, ($0.85y_c$).

11. Wingwalls should be located at an angle of 45° with the outlet centerline and have a top slope of 1 to 1.

12. Modify the approach channel as follows:

    a. Crest of spillway should be at same elevation as approach channel.

    b. Bottom width should be equal to the spillway notch length, $W_o$, at the headwall.

    c. Protect with riprap or paving for a distance upstream from the headwall equal to three times the critical depth, $y_c$.

13. No special provision of aeration of the space beneath the nappe is required if the approach channel geometry is as recommended in Step 12.

The geometry of the undisturbed flow should be considered in the design of a straight drop stilling basin. If the overfall crest length is less than the width of the approach channel, it is important that a transition be properly designed by shaping the approach channel to reduce the effect of end contractions. Otherwise, the contraction at the ends of the spillway notch may be so pronounced that the jet will land beyond the stilling basin, and the concentration of high velocities at the center of the outlet may cause additional scour in the downstream channel.

### 11.10.3.2 Stilling Basin Design Example

Using the same problem as was used to estimate scour at the check dam (Section 11.10.2.2), establish the size of a stilling basin.

Given:

Channel degradation is threatening bridge foundations. Increasing the bed elevation 4.5 ft will stabilize the channel at the original bed level. A drop structure will raise the channel bed and reduce upstream channel slopes, resulting in greater flow depths and reduced velocity upstream of the structure. For this Example, as illustrated by Figure 11-17, the following hydraulic parameters are used:

| | | | |
|---|---|---|---|
| Design Discharge | $Q$ | = | 5897 $ft^3/s$ |
| Channel Width | $B$ | = | 105 ft |
| Upstream Water Depth | $Y_u$ | = | 10.6 ft |
| Tailwater Depth | $d_m$, $Y_d$ | = | 9.5 ft |
| Unit Discharge | $q$ | = | 56 $ft^3/s/ft$ |
| Upstream Mean Velocity | $V_u$ | = | 5.3 ft/s |
| Downstream Mean Velocity | $V_d$ | = | 5.9 ft/s |
| Drop Height | $h$ | = | 4.6 ft |

Find: Dimensions for the stilling basin as shown in Figure 11-18.

Solution:

Step 1 Calculate the Specific Head in Approach Channel:

$$H = y_o + \frac{V_o^2}{2g} = 10.6 + \frac{(5.3)^2}{2(32.2)} = 11.0 \text{ ft}$$

Step 2 Calculate Critical Depth:

$$y_c = \frac{2}{3} H = \frac{2}{3}(11.0) = 7.3 \text{ ft}$$

Step 3 Calculate the Minimum Height for Tailwater Surface Above the Floor of the Basin:

$$y_3 = 2.15\ y_c = 2.15\ (7.3) = 15.7 \text{ ft}$$

Step 4 Calculate the Vertical Distance of Tailwater Below the Crest. This will generally be a negative value because the crest is used as a reference point:

$$h_2 = -(h - y_o) = -(4.6 - 9.5) = +4.9 \text{ ft}$$

where: "h" = total drop from the crest of the drop to the flow line of the outlet channel and $y_o$ is the normal depth in the outlet channel

Step 5 Determine the Location of the Stilling Basin Floor Relative to the Crest:

$$h_o = h_2 - y_3 = 4.9 - 15.7 = -10.8 \text{ ft}$$

Step 6 Determine the Minimum Length of the Stilling Basin:

$$L_B = L_1 + L_2 + L_3 = L_1 + 2.55\, y_c$$

where:

$L_1$ is the distance from the headwall to the point where the surface of the upper nappe strikes the stilling basin floor. This is given by:

$$L_1 = (L_f + L_s) / 2$$

where:

$$L_f = y_c\left\{-0.406 + \sqrt{3.195 - \frac{4.368h_0}{y_c}}\right\} = 7.3\left\{-0.406 + \sqrt{3.195 - \frac{4.368(-10.8)}{7.3}}\right\}$$

$$L_f = 19.7\text{ ft}$$

$$L_t = \left\{-0.406 + \sqrt{3.195 - \frac{4.368h_2}{y_c}}\right\} y_c = \left\{-0.406 + \sqrt{3.195 - \frac{4.368(4.9)}{7.3}}\right\} 7.3$$

$$L_t = 0.8\text{ ft}$$

$$L_s = \frac{\left[0.691 + 0.228\left(\frac{L_t}{y_c}\right)^2 - \left(\frac{h_0}{y_c}\right)\right] y_c}{\left[0.185 + 0.456\left(\frac{L_t}{y_c}\right)\right]} = \frac{\left[0.691 + 0.228\left(\frac{0.8}{7.3}\right)^2 - \left(\frac{-10.8}{7.3}\right)\right] 7.3}{\left[0.185 + 0.456\left(\frac{0.8}{7.3}\right)\right]}$$

$$L_s = 67.5\text{ ft}$$

Then, $L_1$ = (19.7 + 67.5)/2 = 43.6 ft

or $L_1$ can be found graphically from Figure 11-19.

$L_2$ is the distance from the point at which the surface of the upper nappe strikes the stilling basin floor to the upstream face of the floor blocks; see Figure 11-18. This distance can be determined by:

$L_2 = 0.8(y_c) = 0.8(7.3) = 5.8$ ft

$L_3$ is the distance between the upstream face of the floor blocks and the end of the stilling basin. This distance can be determined from:

$L_3 > 1.75y_c = 1.75(7.3) = 12.8$ ft

Step 7 Proportion the Floor Blocks:

a. Height is $0.8y_c$, 0.8(7.3) = 5.8 ft.
b. Width and spacing should be $0.4y_c$, with a variation of ± $0.15y_c$, permitted.
c. Blocks should be square in plan.
d. Blocks should occupy between 50% and 60% of the stilling basin width.

Step 8 Calculate the End Sill Height:

$(0.4y_c) = 0.4(7.3) = 2.9$ ft

Step 9 Longitudinal Sills:

If used, should pass through, not between, the floor blocks. These sills are for structural purposes and are neither beneficial nor harmful hydraulically.

Step 10 Calculate the Sidewall Height Above the Tailwater Level:

$(0.85y_c) = 0.85(7.3) = 6.2$ ft

Step 11 Wingwalls:

Should be located at an angle of 45° with the outlet centerline and have a top slope of 1 to 1.

Step 12 Modify the Approach Channel:

a. Crest of spillway should be at same elevation as approach channel.

b. Bottom width should be equal to the spillway notch length, $W_o$, at the headwall.

c. Protect with riprap or paving for a distance upstream from the headwall equal to three times the critical depth, $y_c$.

Step 13 Aeration of the Nappe:

No special provision of aeration of the space beneath the nappe is required if the approach channel geometry is as recommended in Step 12.

## 11.11 REFERENCES

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